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Oceanography: Exploring Earth's Final Wilderness

Course Guidebook

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PUBLISHED BY:

THE GREAT COURSES
Corporate Headquarters
4840 Westfields Boulevard, Suite 500
Chantilly, Virginia 20151-2299
Phone: 1-800-832-2412
Fax: 703-378-3819
www.thegreatcourses.com

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Professor Harold J. Tobin is Professor of Geoscience at the University of Wisconsin–Madison. He received his B.S. in Geology and Geophysics from Yale University in 1987 and his Ph.D. in Earth Sciences from the University of California, Santa Cruz in 1995. After postdoctoral research at Stanford University, he held a faculty position at the New Mexico Institute of Mining and Technology for 9 years before joining the faculty at UW–Madison in 2006.

Professor Tobin's research specialty is in marine geology and geophysics, especially the geology of deep-sea trenches and the processes of earthquake faulting beneath the ocean. He is a veteran of 10 oceangoing research expeditions and has spent nearly a year and a half of his life at sea, cumulatively, in locations ranging from the equatorial Pacific off the coasts of Panama, Costa Rica, Colombia, and Ecuador; the northeastern Pacific off Oregon, Washington, and Vancouver Island; the Atlantic near the island of Barbados; and off the Pacific coast of Japan. His seagoing work has also included dives to more than a mile below the surface in the submarine *Alvin*. Since 2004, he has been Co-Chief Scientist for the Integrated Ocean Drilling Program's Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE), an ongoing U.S.-Japanese collaboration on the causes of submarine earthquakes and tsunami that is the largest scientific ocean-drilling project in history.

Professor Tobin has published more than 40 papers and articles in scholarly journals, including *Science*, *Nature*, *Geology*, *Journal of Geophysical Research*, and *Oceanography*. He has authored more than 100 abstracts for national and international conferences, and he has also contributed a chapter to the *Encyclopedia of Solid Earth Geophysics*. His work has been featured on television programs such as The History Channel's *Modern Marvels* and

the Discovery Channel's Science Channel special *Exploring Time*, as well as in numerous magazine and newspaper articles.

In 2000, Professor Tobin received NASA's Lyndon B. Johnson Space Center Group Achievement Award for contributions to the astronaut training program. In 2003, he was selected as a Japan Society for the Promotion of Science Fellow. He has been selected twice by scientific organizations as a traveling speaker, giving both public and scholarly presentations across North America: first as a 2005–2006 Joint Oceanographic Institutions Distinguished Lecturer and later as a 2010–2011 Speaker for the EarthScope project of the National Science Foundation. In 2009, he received an award for Best Instructor (University Housing Award) from the students of UW–Madison. In 2007, he was elected as a Fellow of the Geological Society of America. ■

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Oceanography: Exploring Earth's Final Wilderness

Scope:

Earth's single, truly unique, defining feature is the ocean of salty water that covers most of its solid surface to a depth of thousands of meters. For nearly all of the 4.6-billion-year history of the planet, the ocean has existed and has been essential to life, climate, and even to the planet's geological evolution through plate tectonics. This course explores all of these topics and more.

The global ocean is a rich and incredibly diverse environment that has cradled the original development and evolution of life. The ocean continues to control the climate and distribution of heat energy on the planet and hosts vast resources, yet its watery mysteries have only begun to be explored in full. It remains a great research frontier, and the science of oceanography is still a true adventure. It is therefore an extraordinarily rich and varied topic, incorporating all the physical, chemical, geological, and biological sciences in the study of Earth's single vast ocean. In this course, we explore all of these disciplines to understand how they illuminate the ocean and its inhabitants. The overarching theme of the course is the inextricable linkage between the ocean's water, heat, light, chemistry, biology, and geologic and atmospheric processes. It is impossible to understand any one of these topics without considering all of them.

The course begins with an exploration of the physical environment of the ocean and how we have come to know it. Ocean exploration began with Polynesians, Phoenicians, Vikings, and other early traders and settlers who had to solve problems in navigation and mapmaking to achieve their goals. In modern times, exploration technology maps the seabed using sound waves and the surface using satellites. Therefore, we now know that the ocean basins—the containers for the sea—are the result of plate tectonic processes of seafloor spreading at mid-ocean ridges that create the oceanic crust. The plains give way to the shoaling sea floor of the continental slopes and shelves—locations where sediment detritus that is shed off the ever-eroding land is deposited in voluminous accumulation. Along the edges

of some of the ocean basins, deep-sea trenches mark the location at which the destruction of the ocean floor is recycled back into Earth's interior. All of these regions, from the shallowest sunlit waters to the deepest trenches, are habitats for the amazing diversity of organisms that populate every conceivable niche.

Next, we turn to the physical ocean itself—1.3 billion cubic kilometers of water, the properties of which shape life and climate on Earth. All of it has very similar chemistry because currents keep it well mixed, and it remains in a narrow range of temperature. These stable conditions originally allowed life to evolve and exist predominantly in the ocean; life on land is a relatively new development. Light penetrates the upper few hundred meters, and bottom-linked communities—such as coral reefs and kelp forests—as well as open-water plankton are the photosynthesizers and the foundation of the food webs. Darkness reigns below that, and the near-limitless open-water mass supports a diverse ecosystem of pelagic organisms, many of which have no hard parts to their bodies and are virtually transparent. These communities depend on the scavenging of food that rains down constantly from sunlit waters above—as do most of the organisms of the cold, dark, deep sea floor. Perhaps the most fascinating of all bottom communities, however, are those of the hydrothermal hot-spring vents, where life is based on chemical energy rather than sunlight and where key symbiotic relationships feed ecosystems that may be a window into the origin of all life. The adaptations and life strategies of creatures ranging from submicroscopic picoplankton bacteria to fish, invertebrates, and marine mammals interweave to utilize all available energy throughout the entire ocean volume.

All of the water that composes the ocean is constantly in motion. Ocean waves are generated by the drag of wind blowing over water and can travel as swells thousands of miles from where they are generated. Tsunami and rogue waves are special classes of destructive waves, each capable of traveling long distances across the ocean to strike with little warning. In a sense, tides are the longest waves; they result from the gravitational attraction of the Sun and Moon on the ocean's water, modified by the irregular shapes of the sea floor and coastlines.

On longer timescales, the atmosphere and ocean are intimately linked in their motions, driven by the uneven distribution of heat and modified by the Coriolis effect on all movement as Earth rotates on its axis. Together, these 2 phenomena are responsible for both prevailing wind patterns and all the major systems of surface currents in the world, such as the Gulf Stream and the Canary Current. In contrast to the shallow currents, the bulk of the deep water in the ocean moves slowly in great convection systems driven by gravity and the density of saltwater, mixing the ocean on timescales of thousands of years. All these water movements control the conditions for biological productivity.

In the modern era, human activity is beginning to cause major changes in the ocean as a whole for the first time. Intensive fishing is removing predators and prey alike, altering ecosystems. Most of the added heat in the climate system trapped by greenhouse gas is in the ocean, and the sea level is now rising; that rise is expected to accelerate in the coming decades, affecting estuarine habitats, beaches, barrier islands, and wetlands. Sea-level rise combines with human construction activity to extensively modify the natural deposition and erosion processes on coastlines, causing the loss of beaches and natural barriers in many areas. The extra carbon dioxide added to the atmosphere is exchanged with the ocean, making it more acidic, which adversely affects organisms like coral and phytoplankton. Petroleum and natural gas increasingly come from offshore production, and although society depends on these resources, it is also concerned about impacts from oil spills. Finally, the introduction of pollutants into the sea affects coastal regions in particular but, increasingly, the entire ocean as well.

With these pressures on the ocean environment, the rest of the 21st century is undoubtedly going to be marked by growing pressure on its ecosystems, requiring more active stewardship to maintain the health of the entire planet's life-support system. As the course comes to a close, we return to the theme of linkages among all the physical and biological systems in the ocean—and how the study of oceanography weaves them together. ■

Diving In—The Ocean Adventure

Lecture 1

Oceanography is an extraordinarily rich subject that weaves together geology, biology, physics, and chemistry to illuminate the single ocean—vast, deep, and mostly dark—that defines our planet. We will explore the ocean and understand, through the science of oceanography, so much more about the mystery of what lies beneath the surface of the waves. Our ultimate goal will be to understand how human interactions with the ocean take place and what forces govern our interactions with the sea. The ocean remains a great research frontier, and oceanography is still a true adventure.

Earth's Ocean

- Unique in our Solar System, Earth is covered by a liquid water ocean—the most fundamental feature that governs the geology of our planet.

- Earth's ocean governs the biology and development of life on this planet; it also governs so much of human history. Human beings have been fascinated with the ocean for millennia.

- This course is about how all of the different sciences come together in the study of the ocean; the only way to understand the ocean in all of its diverse facets is to bring together a whole range of different sciences.

- Ocean science is fundamentally an adventure because there is so much that is still unexplored, yet there is also so much that we have learned over the course of the past centuries about how the ocean works, how life exists in the ocean, and what is going on both above and beneath the sea floor.

- Earth is a water planet, and 71% of its surface is covered by the ocean. In addition, almost all of the water on the planet is found in the ocean.

- Seawater and saltwater compose 97% of Earth's surface water. All of the freshwater—the polar icecaps, lakes, rivers, streams, and ponds—and the groundwater that supplies our drinking water composes only 3% of the water on the planet.

- For nearly all of the 4.5-billion-year history of the planet, the ocean itself has also been around.

- The ocean has been essential to life; to the climate, what makes Earth a habitable environment; and even to the geological forces of the planet.

- **Plate tectonics**, the motion and evolution of Earth's outer layers, probably would not exist if it were not for the water in the ocean and on the surface of the planet.

- **Oceanography** encompasses all of the natural sciences and applies them to interpret the marine realm.

Types of Oceanographers

- **Physical oceanographers** and **chemical oceanographers** simply apply the principles of physics and chemistry to the study of the water column—the water that is above the sea bottom.

- Marine geologists and geophysicists are interested in how the ocean basins became the way they are and how the shape of the sea floor is a reflection of processes like plate tectonics.

- Marine geologists and geophysicists also study how the record of Earth's climate history is present in the sediments that accumulate over eons on the sea floor.

- Marine scientists and marine biologists study the life that lives in the ocean.

- The biology and the history of life—the paleontology—in the ocean is linked to physical oceanography, chemical oceanography, and geological oceanography.

- **Paleoceanography**, or paleoclimatology, is the study of the state of the ocean in the past, which is typically accomplished through understanding the sediments and the accumulated biological fossils that are found in the sea floor from millions and billions of years ago.

- Mathematical modelers and computer simulation of the ocean are increasingly important.

- Ocean engineers have been around since ancient times in terms of understanding how to build ships and how to navigate the ocean, but today some of the largest structures on the planet are built on the sea floor—such as offshore oil installations or tunnels and bridges—so there are special needs that ocean engineers address, including the pressures and conditions on the sea floor and at great depths below it.

The Science of Oceanography

- The roots of all ocean science lie in the practical needs of predominantly sailors and traders, especially in the early days. Today, the scientists who are looking at satellite imaging have some of the same practical interests: They want to know about the currents in the ocean that are going to drive weather patterns like hurricanes and storms.

- Scientists are driven by a level of curiosity about fundamental science: How does our planet work?

- Scientific curiosity has always existed, but it certainly has come to the forefront over the course of the past century in a way that did not exist before.

- Fundamentally, oceanography is a young science; even 50 years ago, the most basic nature of the deep ocean remained a mystery to us.

- As Earth beneath the sea has gradually been revealed, the origins of the planet and the life on it have come into focus.

- The story of oceanography has played out over recent generations in a way that makes it very much a science that is developing extremely rapidly.

- Different ages of exploration and discovery developed during the history of oceanography.

- The study of oceanography has evolved into an era of measurement in which we can continuously monitor ocean processes; without satellites, monitoring such processes was completely impossible.

Marine Geology and Marine Biology

- The most fundamental thing we have learned in marine geology over the course of the past century is that the ocean floor is the most dynamic geologic environment on Earth.

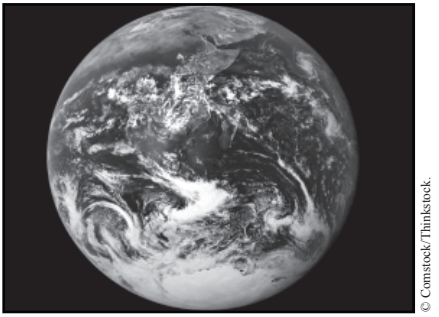
- The sea floor is continuously being remade; volcanoes are constantly erupting under the ocean. In fact, most of the erupting volcanoes on the planet are actually at sea.

- The revolution in Earth sciences that we call plate tectonics has shown us that most of the action of plate tectonics involves the ocean floor—not the continents.

- Marine biology studies the various organisms that live in the sea, which range from the familiar fish to the strange creatures that swim through the deep-sea vents of the sea floor.

Life in the Ocean

- Almost unimaginably varied and filling every niche of depth, temperature, and pressure in the ocean, life has been evolving and adapting in the sea for up to 4 billion years—almost as long as Earth has existed.



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The work of marine biologists, who study ocean life, is an aspect of oceanography that is linked to physical, chemical, and geological oceanography.

- In contrast, life has only been around on land for a relatively short portion of Earth's history.

- Everything that lives in the ocean is connected in a way that is very specific in terms of food webs: The smallest denizens of the sea up to the largest are intimately linked in a continuous energy exchange that we think of as a cycle of production and predation.

- Life itself is possible because of the special properties that water possesses: how water converts from a gas to a liquid to a solid and how those properties control the environment of our planet from the arctic to the tropical regions.

- The chemistry and the physics of this fundamental fluid make Earth special and unique.

The Vast Subject of Oceanography

- We will have to explore chemical and physical oceanography in order to understand everything about how water moves in the ocean, how water traps heat in the ocean, and how water interacts with the atmosphere and with what is below the sea floor in a complex system that we call the ocean.

- We will look at ocean environments and habitats that range all over the planet from ice shelves in the arctic to tropical reefs to the deepest water. We will explore where the energy comes from that fuels life at the bottom of the ocean.

- We will also take a look at the interaction between the sea and the landscape. The sea meets the land at the coasts, and that is a constantly changing environment that is governed by fundamental processes of physics and chemistry. We will also look at the malevolent aspects of how the sea interacts with the land—as exemplified by tsunami.



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The global ocean is a rich and incredibly diverse environment, yet its mysteries have only begun to be explored in full.

The Importance of the Sea

- Understanding the ocean system is critical to understanding how human interactions with the ocean will impact the habitat and the ecosystems that are beneath the sea.

- We rely on the resources that we use from within and beneath the sea; they are critical benefits to human society.

- We get food from the ocean, and we get fuel from the ocean, but the ocean is also a place of recreation.

- In this course, we are going to explore the different aspects of human interaction with the ocean, and we are going to use the science behind chemistry, physics, biology, and even geology to do so.

Important Terms

chemical oceanography: Discipline primarily concerning the composition of seawater and distribution of its chemical constituents.

oceanography: The scientific study of the oceans, encompassing the application of the disciplines of physics, chemistry, biology, and geology to all aspects of the global ocean.

paleoceanography: Discipline that involves studying ancient past currents, climate, and the state of the ocean from thousands to billions of years ago.

physical oceanography: Discipline primarily concerning the movement and physical properties of water in the oceans.

plate tectonics: Scientific theory on the movement and evolution of Earth's outer layers over geologic time.

Suggested Reading

Garrison, *Essentials of Oceanography*.

National Oceanic and Atmospheric Administration (NOAA), *Hidden Depths*.

Prager, *Chasing Science at Sea*.

Sverdrup and Armbrust, *Introduction to the World's Oceans*.

Questions to Consider

1. How do humans experience the ocean today as compared to a century ago?

2. Is oceanography a scientific discipline in its own right, or is it a collection of disparate but related fields?

Explorers, Navigators, Pioneering Scientists

Lecture 2

Human beings have plied the sea for many thousands of years. First, they were driven by a desire for resources, trade, and travel; later, they were driven by a quest for knowledge—an exploration that continues today. Ocean exploration developed early technologies of shipbuilding and navigation, mostly as a byproduct of practical needs. Open-ocean crossings by Polynesian, Nordic, and European seafarers were accomplished through remarkably skilled navigation. The 20th century brought the rise of specialized ocean science, the exploration of the inner space beneath the waves, and major research activity that continues to expand today.

The Dawn of Ocean Science

- By about 1200 B.C., the ocean was an area where accomplished Egyptian, Phoenician, and Cretan sailors were traveling up and down the Mediterranean coastline and beginning to map and chart the regions around them in order to travel by sea.

- During this time, Native Americans were migrating along the Pacific Northwest coast. They were traveling through much more difficult conditions and navigating large parts of the sea in various areas.

- Ancient Phoenecians were exploring open ocean in the Atlantic by around 900 B.C.

- Over a period of 20,000 years, Polynesians were spreading over the Pacific Islands and were traveling long distances by about 2500 B.C.

Voyagers and Technology

- Technology was so important in so many ways to voyagers; in particular, the early technology they needed was for tasks such as shipbuilding: They needed seaworthy vessels in order to venture away from the coastline and protected waters and out into the rougher waters of the open ocean.

- Early voyagers needed some form of navigation: a knowledge of the shape of the coastline but also of the size and shape of Earth as a whole.

- They needed mapping or accurate charts to help find their way: They needed some way to keep a record beyond oral tradition from one navigator to another.

Navigating the Ocean

- The ancient Phoenicians and the ancient Greeks were accomplished travelers.

- In the 3rd century B.C., Eratosthenes created a map of the Mediterranean region that survives today as perhaps the first kind of true mapping and oceanographic chart.

- The key feature of the map is that it orients the map with lines that are similar to modern lines of latitude and longitude.

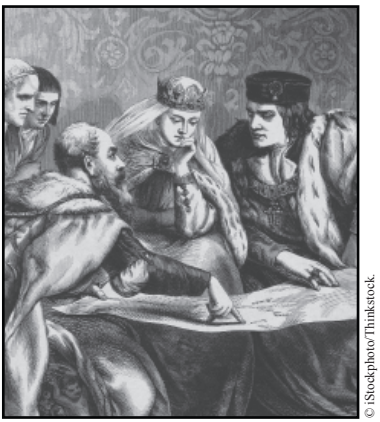
- Eratosthenes knew that Earth was spherical, and he was able to calculate the size of Earth in a remarkably precise way.

Open-Ocean Crossings

- The open-ocean crossings that came about as a result of Mediterranean navigation were accomplished through the development of incredibly skilled navigation that was based on the idea of using celestial reference points to get around.

- The navigators that made the first open-ocean crossings in Europe were the Nordic and Mediterranean seafarers.

- However, the Polynesians are the ones that did it earliest and best in terms of actually crossing large expanses of open ocean in order to populate all of the Pacific Islands that became the Polynesian home—a region in the Pacific Ocean now called the Polynesian triangle.



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Christopher Columbus (1451–1506) never made it to North America, but he opened up a new era that was marked by an explosion of exploration by European merchants and colonists.

- By about 20,000 years ago, it is clear from archaeology that there were islanders dotting the Philippines and the islands of New Guinea who were launching off for seafaring trips increasingly farther afield from those regions.

- Over the course of nearly 20,000 years, during what we consider the Polynesian expansion, these seafarers spread from the region near Asia out across all of the southwestern Pacific and were poised around where the islands of Fiji are today by around 900 B.C.

- Over the course of the following 1400 years, the Polynesians spread to islands all over the southern Pacific as far away as Easter Island.

Improvements to Navigation

- It is clear from the oral history and present-day knowledge of Micronesians and Polynesians—as well as from archaeology—that they had a sophisticated ability to navigate by stars and also by features of the ocean itself and the islands.

- Micronesian **stick charts** are probably very similar to what was used by Polynesians during the expansion. Stick charts are simple networks or lattices of bamboo sticks with shells, which represent individual islands dotting the Polynesian region, that are tied at particular junctures. The curved sticks that are bent onto the stick chart actually represent the refraction of waves around those islands.

- Polynesian navigators also observed the atmosphere because they knew that clouds build up over islands. Even islands that cannot be seen over the horizon have a signature in terms of the clouds that exist there.

- The birds, the smells in the air, and the water would all lead Polynesian navigators toward land—places that they could identify and then sail toward.

Before and After Columbus

- In the Atlantic, the Nordic people in particular were making the open-ocean voyages that discovered the parts of the world beyond the European mainland and beyond the British Isles.

- Viking explorers, especially Eric the Red and his son Leif Eriksson, sailed across the North Atlantic Ocean to Iceland and then beyond to Greenland and even to Nova Scotia and the mainland of North America—a point that Christopher Columbus never reached.

- During the Ming dynasty in China, shipbuilding and navigation were very rapidly advancing. Technologies like the magnetic compass, the central rudder, and the concept of ships with multiple masts and big sails were all invented in China and were ultimately exported to Europe.

- Europe adopted many of these innovations and made some of their own in order to build an increasing number of ocean-worthy vessels.

- Although Columbus never made it to North America in his voyage of 1492, he opened up an entirely new era that was an explosion of exploration by European merchants and European colonists.

- This era of expansion began as a result of new technologies in navigation and shipbuilding, and it was certainly driven by the competition for resources in the new colonies that rapidly opened up after Columbus's day.

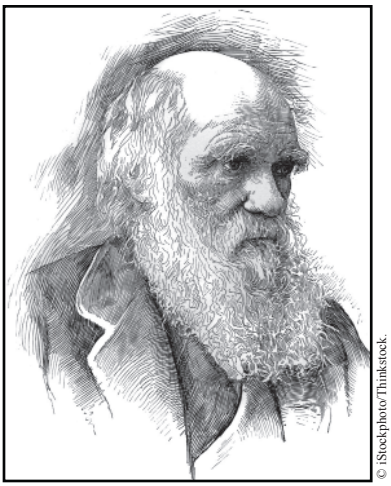
Mapping the World

- If you look at a globe, what you see are lines of latitude and longitude that span Earth. Latitude measures the distance from 0° at the equator to 90° at the pole—north and south. Longitude measures a reference point in meridians around the planet perpendicular to latitude—east and west.

- In order to determine your position of latitude at sea, what you need to do is make a measurement of the angle to a celestial object.

- It was understood even by the ancient Greeks that the North Star hung above the North Pole.

- A **sextant** is a very simple tool that has been around for many hundreds of years. It is a measure of a geometrical angle and is used to determine latitudinal position.



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In the ocean sciences, Charles Darwin (1809–1882) is best known for his theory of coral reefs and atolls.

- Columbus used a sextant to measure the reference angle between the horizon and some celestial object—most typically the North Star—in order to determine how far north or south he was.

- In fact, finding north and south position was exactly how a lot of early sailing was accomplished.

- Finding longitudinal position is a lot trickier because it changes as Earth rotates; over a 24-hour period, Earth goes around a full rotation.

- The secret to measuring longitude is actually in measuring time—much like the reasoning behind the existence of time zones today.

- Therefore, the secret to determining east-west position accurately was for seafarers to keep time well.

- At first, this just meant having a pendulum clock or an hourglass on the ship, but those often lost time.

- John Harrison developed a new way of keeping time in order to determine position at sea. His technological innovation, the **chronometer**, was a windup clock with gears and motions that kept time precisely enough to allow navigation to take place.

- After Columbus, in the 1500s, exploration expanded rapidly. By 1507, the Waldseemüller map was created, which showed that the world size and shape was beginning to come into focus—at least across the Atlantic for the Europeans.

- In 1519, as a result of the advancement of mapping, Magellan set sail from Portugal and made the first circumnavigation of the world; his fleet sailed through the Atlantic Ocean, around South America, and into the Pacific Ocean.

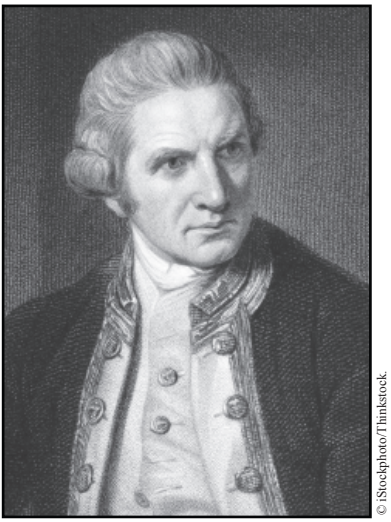
The Underpinnings of Modern Oceanography

- By the 18th and 19th centuries, systematic observations and sampling of the ocean had begun.

- In the 1760s through the 1780s, Captain Cook led the first expeditions that had an oceanographic component. For the first time, there was a systematic observation of natural science that was charted in detail.

- Captain Cook's voyages marked the beginnings of oceanographic science. He and his team took many samples from both the sea and the lands that they visited and recorded them for history. In addition, they discovered many animals.

- Actually, his objective was to discover a hypothesized southern continent that some philosophers believed should balance out the land in the Northern Hemisphere with a very large continent in the Southern Hemisphere.



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In the 1760s through the 1780s, Captain Cook's expeditions marked the beginning of the existence of an oceangoing science.

- In the 1800s, the development of oceanographic science continued with true naturalist expeditions.

- Charles Darwin is famous for his description of life on the Galapagos Islands—of the finches and of the botany—and for his theory of natural selection and evolution, but he was also a phenomenal naturalist and observer of geology.

- Darwin developed a theory of coral reefs and **atolls**. He recognized that there were islands dotting the Pacific that were surrounded by fringing reefs of coral. In some cases, he found islands that were composed of just the reefs themselves, and in other cases, he found atolls, which had no rocky island in the center.

- Darwin came up with a theory that, initially, a volcano surrounded by a reef had slowly subsided beneath the waves, leaving the reef behind as it grew up and stayed in the sunlit zone that it needed for photosynthesis.

- In the 1870s, the HMS *Challenger* expeditions were the first true oceanographic expeditions that documented about 4700 new species and collected many samples.

- At the turning of the 20th century, a voyage led by Fridtjof Nansen—a Norwegian arctic explorer who is one of the most remarkable adventurers and ocean scientists—established the idea that there existed a polar sea.

- By the 20th century, ocean exploration was exploding, and the belief was that to really understand what was going on in the sea, especially the deep sea, one had to visit the bottom.

Important Terms

atoll: Ring-shaped group of coral islands or reefs formed around a now-submerged volcanic island.

chronometer: Precise clock originally used to determine longitude based on timing of local noon.

sextant: Instrument used to measure the angle above the horizon of celestial objects that is used in navigation.

stick chart: Maplike representation of islands, waves, and ocean currents used in navigation by Micronesian and Polynesian seafarers.

Suggested Reading

Darwin, *The Voyage of the* Beagle.

Horwitz, *Blue Latitudes*.

Sobel, *Longitude*.

Questions to Consider

1. What makes a scientist working at sea distinct from an explorer?

2. How might the different geography of the South Pacific versus the Atlantic and Mediterranean regions lead to different kinds of navigational solutions by the Polynesian versus European seafarers?

Ocean Basics and Ocean Basins

Lecture 3

The ocean basins—the "containers" of the sea—are not simply a submerged version of the continents but, rather, have their own unique physiographic features reflecting their geological origin. Major features include the globe-encircling mid-ocean ridge mountain range; deep-sea trenches; vast abyssal plains; and the continental shelves, slopes, and rises. Each major ocean basin—Pacific, Atlantic, Arctic, Indian—has unique architecture, reflecting common processes but differing histories. The deep-ocean floor is underlain by oceanic crust, which is formed exclusively by volcanic processes and is completely different from continental crust.

Ocean Basins: The Containers of the Sea

- As recently as the 1950s, geologists had a conception of the **ocean basins**, the ocean floor itself, as kind of a submerged version of the continents that trapped all of the sediments that came off of the continents in thick accumulations.

- In fact, the oceans are not like this at all: They are their own unique physiographic province, which means that the morphology and shape of the sea floor reflects a unique geological origin of many features.

- Little has been known about the depth and shape of the ocean floor until very recently. We did not know how deep the water was in the deep sea until the late 1800s.

- The turning point in massive data collection in the oceans was the explosion during, and then after, World War II with new instruments and new amounts of trade going on all around the planet.

Land versus Sea

- If we look at Earth's elevation, we can say that it does not come in some random distribution of land and sea. The elevation of the surface of the planet above or below sea level is not random, either. In fact, it comes in 2 different modes: continent and ocean, each of which represents different kinds of crust on the planet.

- The oceans reach depths in the **deep-sea trenches** that represent just a vanishingly small area of the oceans but that reach very large depths—as deep as 1100 meters below sea level.

- The ocean basins are dominated by broad, deep, flat plains that have a depth of about 3000–5000 meters.

- In addition, there is a defined slope and then broad, open areas we call the **abyssal plains** that are the vast majority of the open-ocean basins.



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The Arctic Ocean is the smallest of the major ocean basins, composing only 2.4% of the world's surface area.

- The average depth of the ocean is almost 4000 meters below sea level, and the average elevation of land above sea level is about 840 meters.

- The land is distributed in an exponential way from the coastline up to the highest elevations with less and less at each higher elevation until you reach the peak of Mount Everest or the Himalayas, in which case a tiny fraction of the land is that high.

- A **hypsometric curve** shows graphically the distribution of elevations on the planet.

- The volume of the sea is much greater than the volume of all of the land above sea level on the planet; the ocean basins greatly exceed the continents in volume.

- The different geology of the ocean floor compared to the continents creates the fundamental difference between the 2. The ocean floor is much thinner as a crust than the continents, and it is also much denser than the continents.

- In general, continental rocks are less dense than rocks found on the oceanic floor, which makes a difference in the elevation that they attain.

Features of Ocean Basins

- The world's oceans—the Atlantic, the Pacific, the Indian, and the Arctic are the major ones—are all actually one ocean.

- The boundaries that separate the world's oceans are arbitrary because there is a deepwater ocean-floor connection among all of the ocean basins.

- In fact, there is a globe-encircling **mid-ocean ridge** mountain range. There are also deep-sea trenches all around the world, and then there are vast abyssal plains. In addition, there are continental shelves, slopes, and rises that connect the continents to the oceans.

The Pacific Ocean

- The Pacific Ocean composes 50% of the total ocean area. It is deeper, on average, than the other oceans by a few hundred meters.

- The Pacific Ocean has a mid-ocean ridge called the East Pacific Rise, which is a broad, gently sloping region that rises up thousands of meters above the surrounding abyssal plains, comes up through the Pacific Ocean to the west of South America, and actually runs into North America just at the Baja California peninsula.

- The mid-ocean ridge is, in some sense, the largest or most continuous feature of the bedrock geology of the whole planet. It is essentially a mountain range or mountain chain that starts at an arbitrary point and encircles the entire globe.

- The Pacific Ocean also features thousands of islands, seamounts, and atolls. All of these are part of the **oceanic crust**, and they are essentially all originally volcanoes that formed by processes of volcanic eruption that build up an island off the deep-sea floor thousands of meters until it reaches the surface.

- If a volcanic edifice does not make it all the way up to the surface of the water, we do not call it an island, of course. Instead, it becomes a mountain in the sea—or a **seamount**.

- The Pacific Ocean is also ringed by deep-sea trenches, which is a major difference that is not found in the Atlantic Ocean.

- The deepest places in the ocean are all around the regions of the western Pacific: the Japan Trench, the Mariana Trench, and the Tonga Trench.

The Atlantic Ocean

- The Atlantic Ocean is the second largest ocean on the planet at 1/5 of Earth's surface area—less than 1/2 the size of the Pacific Ocean.

- The Atlantic Ocean is especially remarkable because, if you were to close it up, the continents that would then be touching would fit together like a puzzle.

- The center of the Atlantic Ocean is the Mid-Atlantic Ridge, which is a high mountain range that is composed of virtually all seamounts below the surface of the water.

- The Atlantic Ocean shares with the Pacific the existence of abyssal plains and a water depth in excess of 4000 meters.

- Where the Atlantic Ocean differs from the Pacific Ocean is the lack of real deep-sea trenches; instead, there is a smooth, continuous connection between the abyssal plains and the continents that surround it on both eastern and western sides.

The Arctic Ocean

- The Arctic Ocean is north of the Atlantic Ocean and is the smallest of the major ocean basins, at only 2.4% of the world's surface area.

- However, it is a major ocean basin because it has true deep water—that thousands of meters deep abyssal plain morphology of the sea floor that was formed as true oceanic crust through the ocean-floor volcanic processes.

- Until the early part of the 20th century, the Arctic Ocean was not even known to be an ocean. We now know that it is an ocean basin with currents that connect the Atlantic to the Pacific Oceans.

The Indian Ocean

- The Indian Ocean is the third largest of the ocean basins. It has the Southwest Indian Ridge in the center, which is a continuation of the Mid-Atlantic Ridge and the East Pacific Rise that has high elevations at the center with abyssal plains on either side.

- The Indian Ocean is very similar to the Pacific and the Atlantic Oceans in its general sea floor morphology; it is surrounded by some continental shelves and slopes and contains a deepwater ocean basin formed by oceanic crust—all of which are continuous with each other.

The Southern Ocean

- Antarctica, located at the South Pole of the planet, is a land mass that is completely encircled by open, deep water.

- Sometimes this is referred to as a fifth ocean called the Southern Ocean, but in actuality, it just encompasses pieces of the Atlantic, the Pacific, and the Indian oceans.

- The Southern Ocean clearly illustrates how the entire ocean is one great circulating mass, and in fact, we are surrounded by the ocean—and by deep ocean basins.

One Ocean

- The single ocean that covers the entire planet has common processes all over it, and each major ocean basin was formed by these oceanic crust–forming processes, or plate-tectonic processes, but each one also has different histories and, therefore, different morphologies.

- For example, the Pacific Ocean has deep-sea trenches whereas the others do not. The other big distinction among the different ocean basins is the shape of the mid-ocean ridge, which reflects different rates and speeds of plate tectonics that are occurring in different parts of the planet.

Continental Margins

- At the edges of the continents, we know that the land does not just abruptly drop off in a gigantic cliff down to the base of the abyssal plain; rather, there is a continuation of the continent offshore in what is called the **continental shelf**.

- The continental shelf is connected to the abyssal plain of the deep ocean basin by what is known as the **continental slope**, which has a slope angle of only a few degrees.

- Different **continental margins** around the planet reflect plate tectonic processes and other geological workings that have shaped them into the kinds of continental shelves and margins that they are.

- Continental shelves are fundamentally extensions of the landscape on shore, and they extend quite a long distance offshore in many regions. They are defined as having a water depth of 0–200 meters.

- Continental shelves often have canyons or valleys that were carved by rivers when the sea level was lower and that have been drowned as the sea level has risen.

- Basically, the continents extend out to the continental shelf edge. Sediments are shed off the landscape and delivered to the continental edge by rivers, streams, or the wind.

- The sediments end up in the shallow water on the continental shelf, and then waves and currents move it farther offshore and ultimately shed it to build up the large sediment accumulations that represent the continental slope.



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The world's major oceans—the Atlantic, the Pacific, the Indian, and the Arctic—comprise a single ocean, and their boundaries are arbitrary.

- In places where large amounts of sediment are being dumped into the deep ocean, an accumulation of sediment builds up at the base of the continental slope—almost like a deep-sea delta—that is called a **deep-sea fan**.

- Deep-sea fans extend all along the coastline and will eventually coalesce; over time, they build up a gently sloping lower end of the continental slope, which is referred to as the continental rise.

Important Terms

abyssal plain: The vast, open expanse of relatively level bathymetry that comprises most of the ocean floor.

continental margin: The offshore region extending from sea level to the abyssal plain; comprised of the continental shelf, slope, and sometimes rise.

continental shelf: The offshore extension of the land of nearly flat average slope, extending to a depth of about 200 meters.

continental slope: The relatively steeply sloping region of the ocean floor that extends downward from the shelf edge to meet the abyssal plain.

deep-sea fan: Accumulation of a wedge- or fan-shaped pile of sediment at the base of continental slopes.

deep-sea trench: Narrow, arcuate features extending thousands of kilometers of especially deep bathymetry that form at subduction zones, where oceanic crust bends to descend into the mantle.

hypsometric curve: A graph showing the cumulative area of Earth's surface above any given elevation, above or below sea level.

mid-ocean ridge: The globe-encircling mountain range where seafloor spreading occurs by volcanic activity creating new oceanic crust.

ocean basin: The container for the ocean; the region underlain with oceanic crust and bounded by continental slopes.

oceanic crust: The crust of Earth, which is formed at mid-ocean ridges by lava and magma welling up from the mantle that forms the geologic substrate of most of the ocean floor.

seamount: Volcanic mountain that rises above the surrounding ocean floor but is submerged below sea level.

Suggested Reading

Garrison, *Essentials of Oceanography*, chap. 4.

Kaharl, *Water Baby*.

Kunzig, *Mapping the Deep*.

Questions to Consider

1. If sea level dropped so far as to expose the entire area of the continental shelves, would that represent a large or small change in the total volume of the ocean?

2. Could a submarine traveling only in water deeper than the continental shelves travel though all the world's oceans in one continuous voyage? That is, are any of the deep-ocean basins entirely isolated from the others?

Mapping the Sea—Soundings to Satellites

Lecture 4

Earth's ocean floor is less well mapped than the surfaces of the Moon or Mars because of its great depth and the fact that light and radar cannot penetrate the water. Major basic features of the ocean floor were completely unknown until the late 19th century. Features as large as undersea mountains are still being discovered today—through the progression of methods from line and weight sounding to acoustic echo sounding and sonar mapping to satellite altimetry. Modern oceanographic instruments digitally record currents, temperature, pressure, and salinity all over the world, mapping out the water itself.

Studying the Deep Ocean

- The deep ocean, far away from the shoreline, is a pretty difficult place to study. Access is limited, so you either need boats or measurements from satellites (or airplanes) in order to study it.

- Even today, the ocean floor—at 3/4 of the planet's solid surface—is less well mapped than the surface of the Moon or Venus or Mars because light and radar cannot penetrate the water, so we cannot measure it with the same tools that we use for ordinary observations.

- In the 17th, 18th, and 19th centuries, biologists believed that life could not exist at all at great depths. Even into the late 20th century, they believed that life was at best very sparse in the deep ocean, limited by the small amount of nutrients available.

- It turns out that both of these fundamental assumptions about how the deep ocean works were false. It took new means to access the ocean floor and to gain the understanding that it is a dynamic environment both geologically and biologically—and, in fact, is among the most dynamic environments on the planet.

Measuring the Deep Ocean

- **Bathymetry**, the measurement of the depth below sea level, is an inverse mirror of topography on land.

- Line sounding is the oldest and most obvious method of measuring the depth of the ocean. It involves taking a rope—as long as you have available—attaching a weight to the end of it, and lowering it over the side of a ship until you feel that it hits bottom.

- Understanding the true depth of the deep ocean was something that people with ropes fundamentally could not do for a few reasons: in deep water, it is difficult to actually feel the bottom even if you have a rope that long, and the ocean has currents in it that would affect the placement of the rope.

- In order to address this problem, by the 1830s, the U.S. Exploring Expedition launched the first wire soundings in which they wheeled a wire line—a cable instead of a rope—off some kind of winch, attached a cannonball to the end of the wire, and sent it down to the bottom rapidly. They timed the speed of the line as it left the reel, which would decrease when the cannonball hit the bottom.

- In addition, these explorers would paint a small amount of grease onto the bottom of the cannonball so that it came back up with a tiny sample of what was on the sea floor to prove that they had hit the bottom. In fact, this was the first way in which the deep ocean sea floor was sampled in any way.

- By 1854, using this wire-sounding method, Lieutenant Matthew Maury made the first map of the Atlantic Ocean in terms of the depth of the water. The map contained many erroneous soundings because it is so difficult to make these soundings that not many measurements were made.

- The next breakthrough step in mapping the ocean floor was accomplished by the HMS *Challenger* expedition in the 1870s. These explorers used a hemp line that was mechanically winched over the side so that it was a very light line with a very heavy weight attached to it. They also included a sampler that would take a plug of whatever was on the sea floor.

- In fact, these early oceanographers measured a depth of nearly 5,000 fathoms—a unit of length equal to 6 feet—or 8,180 meters in the Mariana Trench in the Pacific Ocean. This was the first recorded observation that there was such a thing as a deep-sea trench.

Mapping the Sea Floor

- In the 1920s, the act of mapping the sea floor was transformed with the invention of **echo sounding**, which provided an acoustic measurement of depth.

- The echo sounder offers a couple of great advantages to mapping out the sea floor: It is an almost instantaneous measurement, so many measurements can be made, and it produces a continuous profile of the sea floor because it can be done while the ship is constantly sailing as opposed to having to stop.

- An echo sounder relies on the fact that the speed of sound in water is virtually a constant number: 1500 meters per second, plus or minus about a percent.

- To measure depth with an echo sounder, you send out a ping of sound from the bottom of a ship, and then you wait for that to bounce off something—usually the sea floor. You then measure the delay time, or the travel time, and 1/2 of that time is the depth of the water if you multiply it by the speed of sound in water.

Historic Seafloor Discoveries

- In 1925, the German research vessel *Meteor* profiled the sea floor and detected the Mid-Atlantic Ridge for the first time.

- The use of echo sounders really took off in World War II with the allied war efforts sending many vessels, both merchant and military, back and forth between the United States, the United Kingdom, and Europe.

- The military vessels that traveled in the Pacific Ocean were equipped with echo sounders that detected deep-sea trenches, seamounts, and abyssal plains for the first time.

- The terrain of the ocean floor was finally coming into focus—a feat that was of great military use because, for example, they wanted to be able to find places where rival submarines could be hiding.



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Ocean drilling—for oil and gas—actually began as a scientific project to drill into Earth's mantle at sea; in fact, scientific ocean drilling continues today.

- What revolutionized our understanding of the ocean floor—and revolutionized Earth sciences through the mapping of the sea floor—is the work done by 2 people who were working at Columbia University's Lamont Geological Observatory in New York: oceanographer Bruce Heezen and geologist Marie Tharp.

- In the 1950s, Heezen and Tharp created a map of the ocean floor that showed the shape and contours of the Mid-Atlantic Ridge, abyssal plains, and even the continental shelves and slopes for the first time.

- In the 1960s, the military developed new methods of mapping. The information obtained through classified mapping operations in the 1960s did not become available to oceanographers until the early 1990s.

- One of these methods is something that we use today to map out the sea floor called **multibeam bathymetry**, which was developed by the navy and is similar to an echo sounder.

- Using multibeam bathymetry, which we know now by the brand name Seabeam, a ship uses a series of acoustic pulsers that send out a very narrowly focused beam of sound energy. In this way, oceanographers could map out a swath of the sea floor in a lot more detail than was ever possible before.

- The echoes are more focused, so the precision is higher, and it could map out an area instead of a particular spot. The region that it can cover is about 3 times whatever the water depth is.

- Multibeam bathymetry is an ultrahigh-resolution method and is still the best we have today, but it is very labor intensive and expensive. Even today, only about 10% of the ocean floor has been mapped by this method.

Using Satellites to Map the Sea Floor

- One way that we can reach the whole ocean at once is through satellite measurements.

- The 1980s brought the dawn of something called **satellite altimetry** in which a satellite called Geosat and its successors were sent into space with the goal of preceisely measuring the surface height of the ocean instead of mapping out the sea floor.

- These satellites pass over the world and measure the distance from the satellite to the sea surface using a radar signal. The radar signal is accurately timed to measure the elevation of the surface above or below sea level as the tides go up and down.

- The purpose of these satellites was actually physical oceanography—to map ocean currents, subtle differences in sea-surface elevations, and tides in great detail. The unexpected benefit was to generate our modern maps of the ocean floor in a level of detail that was unprecedented before that.

- In 1997, oceanographers Walter Smith and David Sandwell published the first map of the world's ocean based on gravity anomalies measured by radar-based satellite altimetry measurements, giving us a spatial resolution that was unprecedented for the ocean at the time.

- This mapping of the global topographic relief in the ocean and topography on land has been refined several times since the 1990s; with better satellite measurements, whole undersea features of almost unimaginable scale were mapped out that were previously unknown.

Sampling the Sea Floor

- A more sophisticated way to sample the sea floor in a particular spot so you are not just getting a grab bag of material in a dredge is to use either a box corer or a piston corer, which are used to take an actual core sample of the sea floor.

- The piston corer is a simple device, but it has led to our understanding of, for example, the history of ocean currents and ocean climate by looking at the individual sedimentary layers that have been laid down over time—known as a **piston core**.

- The piston corer is a long tube with a heavy weight at the top that is lowered over the side of a ship and, in fact, dropped in almost freefall from a winch. As it plunges into the sea floor, a trigger releases, and a hydraulic piston drives it down into the ocean floor very quickly with a lot of force.

- Ocean drilling began as a scientific project, and in fact, scientific ocean drilling continues today. Ocean drilling began in 1960 with **Project Mohole**, an attempt to drill into Earth's mantle at sea.

- The Integrated Ocean Drilling Program has now sampled thousands of sites all over the world's ocean. *JOIDES Resolution*, and its Japanese counterpart *Chikyū*, are mainstays of scientific ocean drilling and of marine geology.

- Modern ocean science is certainly a high-tech operation, but remote sensing and computer simulations and calculations cannot replace expeditions—we still need to go to the sea to collect data and samples.

Important Terms

bathymetry: Measurement of water depth below the sea surface; an inverse equivalent to topography on land.

echo sounding: Determination of bathymetric water depth by precise timing of a sound wave emitted by a ship and reflected from the water bottom.

multibeam bathymetry: Bathymetric mapping done by echo sounding using a fan of narrow acoustic beams to image a strip of the ocean floor.

piston core: A cylindrical sample of the ocean-floor sediments taken by lowering a hydraulically activated, weighted sampling tube from a surface-research ship.

Project Mohole: The first deep-sea drilling research project; a pioneering but ultimately unsuccessful 1961 effort to drill down to Earth's mantle in the Pacific Ocean.

satellite altimetry: Measurement of the elevation of the sea (or land) surface precisely using space-based radar-signal reflection timing.

Suggested Reading

Garrison, *Essentials of Oceanography*, chap. 4.

Heezen and Hollister, *The Face of the Deep*.

Lawrence, *Upheaval from the Abyss*.

Questions to Consider

1. Was mapping the bathymetry of the deep-ocean basins in the 19th and 20th centuries of any practical use?

2. Why haven't satellite-based measurements entirely replaced sea-going expedition measurements of physical oceanographic data? Do you think they ever will?

Habitats—Sunlit Shelves to the Dark Abyss

Lecture 5

Just as on land, life in the ocean depends on habitat. Key ingredients for living organisms are light, nutrients, temperature, pressure, chemistry, and substrate. The geomorphology of the sea floor governs benthic habitats from the littoral zone to the abyssal zone. Wide, sunlit continental shelves host the most abundant life. Deep and completely dark continental slopes and abyssal plains host a surprising diversity and abundance of life, too. Special environments host entire ecosystems not based on the Sun's energy but rather on plate-tectonic energy from Earth.

Life in the Ocean

- Life in the ocean depends on habitat, just as it does on land. It ranges from the seemingly limitless volumes of open water with no boundaries to very specific ocean-floor environments—from the surf zone to the deepest and darkest of the ocean trenches.

- The ocean is the original habitat on Earth. Life has existed on the planet for 4.6 billion years, but for almost all of that time, it was exclusively in the sea; in fact, no life existed on land for about 75% of Earth's history.

- A **habitat** is the physical environment that is occupied by some organism—the place where it lives and grows.

- The geology of the ocean floor and the physical and chemical conditions of the water define marine habitats.

- Every living organism on the planet needs an energy source. There are primary energy sources—such as light or perhaps chemical energy—that are used by organisms.

- There are also secondary energy sources, such as the food that we consume. Human beings are not great at using primary energy sources; instead, we take up energy that has been turned into food by other organisms.

- Life on Earth also needs a whole variety of chemical nutrients: the chemical building blocks for the metabolic processes that go on in our bodies or in the bodies of any organism, whether it is at sea or on land.

- The key ingredient for many living organisms involves the physical environment: the temperature and the pressure, which is especially applicable to organisms in the ocean.

- Some organisms need a **substrate**, a physical space to live and attach itself. For others, the water itself, or the fluid medium, is a substitute for the substrate.

Marine Environments

- There are 2 ways of dividing the marine environment: the physical location versus dividing by depth, and open water versus the water at the bottom of the ocean.

- In terms of depth, the ocean is a simple 2-layered system: a shallow, warm, sunlit layer—a layer through which light penetrates—and a deep, cold, dark layer through which light does not penetrate.

- The shallow zone that is sunlit is called the **photic zone**; by contrast, everything below the photic zone is called the **aphotic zone**—the zone without any light.

- The vast majority of the deep ocean is completely dark except for light that is generated by organisms themselves, and the availability of light is directly dependent on depth. In addition, the deep ocean is cold, and the pressure increases as you go deeper through the water.

- Light is the defining feature for these zones of water because many marine organisms are dependent on light for photosynthesis—just as on land.

- A second way of classifying marine environments is to consider the proximity to the coastline and to the bottom of the ocean. The open-water environment that is out in the open ocean and is not near the bottom of the ocean is called the **pelagic** ("open sea" or "open water") environment.

- The pelagic environment is broken down into 2 provinces. The **neritic** province is the water that lies over the continental shelves—the shallow water near the shores. For the most part, this province is part of the photic zone, although not entirely.

- Most of the rest of the vast volume of the ocean in the open water is referred to as the oceanic province. In fact, oceanographers commonly use the term pelagic to describe this area. The oceanic province is the open water that is off the continental shelves, far away from the land, and is nowhere near the bottom of the ocean.

- The **benthic** environment is the environment that is in, on, or associated in some way with the sea bottom. This region can be broken down into regions near the shore—near the coast and continental shelf—versus the deepwater, offshore regions.

- All the places along the continental shelf are areas that are in proximity to the coast. Portions of those that are the benthic environment are referred to as the beach itself, or the benthic littoral zone.

- The supralittoral zone is the zone that is, most of the time, out of the water except at the highest tides or in big storms. The littoral region is the beach itself, and the sublittoral zone is the immediate offshore region—in the low tide and just below.

- These zones are sometimes referred to as supertidal, subtidal, and tidal regions. Basically, they are the transition zones between the land and the offshore organisms that reside in proximity to the bottom.

- If we go into the deep water, moving off the continental shelf and into the open ocean, then we go through different benthic zones that are simply defined by their depth: **bathyal**, **abyssal**, and **hadal**.

- The bathyal is the zone that is encountered once you leave the continental shelf at a few hundred meters and down to a few thousand meters—down the continental slopes and rises.

- To an oceanographer, the abyss has a very specific definition. Abyssal depths are depths between about 3000 and 5000 meters of water depth. Approximately 50% of Earth's surface is composed of abyssal benthic habitat.

- There is an even deeper zone in the ocean that only amounts to a few percent of the total ocean floor and is where the deep-sea trenches lie. From about 5000 meters down to the greatest depths of the bottom—called the Challenger deep at around 11,000 meters—is the hadal zone.

A Tour of Organisms

- In the pelagic photic zone, the open water where the sunlight shines on the water, there are the neritic and the oceanic zones. This is where many of the large-scale organisms live: tuna, sharks, skates, rays.

- The pelagic photic zone also includes all of the microscopic organisms that photosynthesize such as various kinds of plankton, which are predominantly microscopic and mainly move by drifting with the seas (drifters).



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Sharks are pelagic organisms, which means that they live in the open water. They are also nekton, which means that they swim actively and independently of currents.

- Examples of plankton are diatoms and dinoflagellates, which are responsible for much of the photosynthesis on the planet and are the basis of the marine food chain. Bacterial plankton are also an important part of the photosynthetic system.

- In addition, zooplankton include such organisms as krill, small shrimp, and jellyfish. All of them are small enough to be drifters, so they are therefore defined as plankton.

- We can contrast the plankton with the nekton, which is the biological term for the active swimmers, the organisms that can move independent of currents.

- There are all kinds of pelagic fish that are nekton: salmon, sharks, tuna, herring. There are also marine mammals—such as manatees, dolphins, whales—and marine reptiles such as sea turtles.

The Deep Pelagic Zone

- The deep pelagic zone can be broken down into different depths, but the whole deepwater zone is dark, has high pressure, and is populated with organisms that live in a world without boundaries.

- There are very few or no currents and no hard objects to bump into. There is nothing to define space; it's essentially a limitless, 3-dimensional volume.

- Various jelly-like creatures that can spread out over large areas and that have a protoplasmic shape are found at these depths. An example is an organism called a pteropod, which is a soft snail that has no shell. There are also many invertebrates and fish that inhabit this dark, abyssal depth.

- Benthic habitats range from rocky tide pools, sandy beaches, and salt marshes to coral reefs, deep-sea floor, and seamounts to exotic environments that have only recently been discovered—such as abyssal deep-sea hot-spring vents, oil seeps, and deepwater mounds.

- By definition, benthic organisms are bottom dwellers. Epifauna live on the sea floor and include fish (flounder, halibut, hake, rattails), invertebrates (snails, mussels, anemones), and plants and algae (seaweed, sea grass). Infauna live buried within the sediments (clams, worms, bacteria).

Environment and Substrate

- The environment and the substrate of the sea floor govern these benthic habitats from the littoral zone down to the abyssal and hadal zones.

- There are many contrasting examples depending on the physical environment. On a sandy beach that is washed by waves, the sand itself is a difficult environment to live in, but horseshoe crabs and clams live there. Starfish and worms live in the deep, muddy ocean floor, where everything is more static.


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Jellyfish are classified as zooplankton because they are passive floaters or drifters. They are limited in locomotion, and some become very large—tens of meters in length.

- The wide and sunlit continental shelves have the most abundant benthic ecosystems, including coral reefs, kelp forests, and sea-grass forests.

- When we think of photosynthesis, we tend to think primarily of plants and trees on land, but it is an equally important process in the ocean habitat, and an equal amount of photosynthesis occurs at sea as on land.

- Coral reefs live near the surface of the water because the corals host, for example, photosynthetic algae that provide most of the food for the corals. Phytoplankton is another example of the basis of the marine food chain being dependent on light existing in shallow water.

- Deep and completely dark continental slopes and abyssal plains host a surprising diversity and abundance of life, too—including many recently discovered organisms.

- Just like in the shallow water, the substrate—the rocky versus muddy or sedimented regions—exerts a primary control on the ecological communities that live there, so different organisms can live with the existence of different geological substrates.

- Rocky substrate provides an anchor for sessile organisms such as crinoids and sea fans. At the bathyal depth, deep-sea sponges and soft corals exist on rocky substrate. Soft, muddy sediment substrate favors scavengers and burrowers.

- Special environments, such as deep-sea vents, host entire ecosystems not based on Sun's energy but rather on plate-tectonic energy from Earth.

- We can think of Earth as a set of interconnected systems that are all linked by the flow of energy, water, and carbon—and other nutrients that are essential for life—through the entire ecosystem, making our planet whole.

Important Terms

abyssal: Depth range of 3000–6000 meters in the water or on the bottom of the ocean.

aphotic zone: The range of water depths into which no sunlight penetrates; the dark zone of the ocean.

bathyal: Depth range of 1000–3000 meters in the water or on the bottom of the ocean.

benthic: The environment on or in close proximity to the bottom of the ocean.

habitat: The physical environment in which an organism lives.

hadal: Depth range greater than 6000 meters in the water or on the bottom of the ocean; the deepest locations in the ocean.

neritic: The region on or over the continental shelf.

pelagic: The open-water environment that is away from coasts and off the continental shelf.

photic zone: The sunlit upper layer of ocean water.

substrate: The sediment or rock base forming part of a benthic organism's habitat.

Suggested Reading

Carson, *The Sea around Us*.

Sverdrup and Armbrust, *Introduction to the World's Oceans*, chap. 14.

Questions to Consider

1. Of the habitat zones discussed in the lecture, which is the largest in volume? How uniform or varied do you suppose the nature of this habitat is?

2. To what extent might ocean habitats have changed over long periods of geological time? How might they be changing now, during the next decades, or future centuries?

The Spreading Sea Floor and Mid-Ocean Ridges

Lecture 6

Plate tectonics explains that the ocean basins are different from the continents because they form through seafloor spreading at the mid-ocean ridges. Mapping of the Mid-Atlantic Ridge contemporaneously with the development of radioactive decay dating of rocks and of rock magnetism led Harry Hess and others to propose seafloor spreading in the 1960s. Alternating stripes of magnetized rocks due to Earth's magnetic reversals through time added support to the theory. Crust gets older symmetrically on either side of ridges, and ocean basin rocks are geologically very young in relation to continents.

The Geology of the Ocean Floor

- It is an underlying process that creates ocean basins in a very specific way, and it is the fundamental theory of plate tectonics that provides the answers to understand why the Atlantic, the Pacific, the Indian, and the Arctic oceans are shaped the way that they are.

- Up to the 1960s, geology was a land-based science. Marine origin of many sedimentary rocks was recognized for centuries; however, continents were generally regarded as fixed in place.

- In addition, crustal motion and deformation was thought to be largely driven by gravity, and ocean basins were conceived as submerged continents, accumulating thick sediments over Earth's long history.

- All of this proved to be wrong, and the story of how geology got its modern form is intertwined with the discovery of the sea floor.

Historical Perspectives of the Ocean Floor

- In the 1500s, Leonardo da Vinci was one of the first to note that there seemed to be something coincidentally odd about how across the Atlantic Ocean you could match up the boundaries of North America, Africa, and South America. It was as if you could close up the Atlantic Ocean and have all of the continents fit together.



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Francis Bacon (1561–1626) noted the fact that the Atlantic Ocean looked like it could be closed up so that the continents would fit together to form a single continent.

- In the 1620s, Francis Bacon noted the existence of this puzzle effect with the continents, and so did Edward Suess, a Swiss geologist of the 1800s. This was generally not taken as more than a curiosity for a long time because there was no explanation of how the continents might have moved.

- In 1915, German meteorologist Alfred Wegener proposed the first real theory of **continental drift**. He bolstered it by gathering different geological evidence—including matching zones of fossils from South America into Africa—that suggested that the continents had somehow separated over time.

- Wegener hypothesized that the evidence required that all of the continents were once assembled as one super continent, which he called Pangaea. It was surrounded by one single ocean, which he referred to as **Panthalassa** after the Greek word for ocean or the sea.

- The idea of continental drift was debated, but ultimately it was essentially rejected by the scientific communities in Europe and North America.

- The Atlantic Ocean has a symmetrical pattern about it with the central ridge and the abyssal plains to either side. Is that not somehow also a coincidence, along with the fit of the continents?

- In 1960, Princeton geologist Harry Hess proposed that new sea floor was continuously being formed by volcanic processes at the Mid-Atlantic Ridge—and perhaps at other ridges around the world—and then were spreading outward equally in both directions from a central ridge or central valley at the top of the ridge.

- Hess further proposed that some kind of convection currents in Earth's interior were pulling the ridges apart such that new magma, new lava, could be erupted at the surface at the ridges.

Evidence for Seafloor Spreading

- In 1957, the map created by Heezen and Tharp showed that there was an incredible level of detailed symmetry about the Mid-Atlantic Ridge. This simple mapping of the seafloor terrain started a scientific revolution.

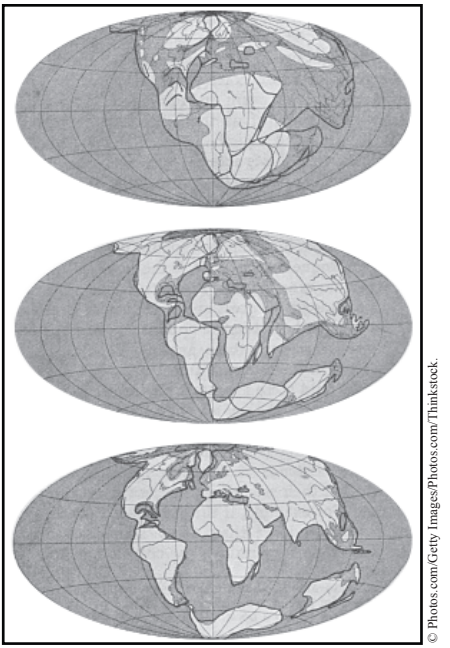
- One of the key observations was the development of a new instrument called a **magnetometer** that could be used by marine geophysicists to measure the variations in the strength of Earth's magnetic field, which is not uniform everywhere.

- In 1963, in a seminal paper for the plate-tectonic revolution, Vine and Matthews proposed that the variations in Earth's magnetic field confirmed Harry Hess's hypothesis of seafloor spreading.

- Vine and Matthews already knew that when rocks were formed from lava—when lava was erupted and then cooled on the surface of Earth—the rock contained magnetite, which is a mineral that is magnetic and is susceptible to the magnetic field.

- On the day or in the weeks that the rock was cooling, the crystals of magnetite in the rock would align themselves with the magnetic field. When these magnetite particles are aligned with the magnetic field, they add a little bit of extra strength to that field.

- Vine and Matthews recognized that perhaps the Earth-dipolar field—because of the swirling motion of Earth's core—actually reverses its field strength at different times in Earth's history. This would cause the North Pole to become the South Pole, and vice versa.



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German meteorologist and geophysicist Alfred Wegener (1880–1930) proposed the first real theory of continental drift, speculating that the coasts of eastern South America and western Africa were once joined.

- If that is true, then the magnetic fields that are locked into the rocks would form an alternating pattern: When Earth's magnetic field is the same as it is today—and the rocks have locked in what we call normal polarity—then the magnetic field strength measured by a magnetometer would be a little bit high.

- Vine and Matthews proposed that the strange stripes of high and low magnetization that are found on the sea floor were the signature of continuous formation of the crust of the ocean floor in times of normal and reversed polarity.

- Because the periods of normal and reversed polarity oscillate at different paces over geologic time, there exists a barcode for the ocean floor: a series of stripes of different thickness and width and in certain patterns that are recognizable anywhere in the world.

Radiometric Dating and Magnetic Information

- During this same timeframe—in the 1940s to the early 1960s—a couple of other things were becoming very clear to the scientific community.

- One really key factor was the development of radiometric dating, or using isotopes of radioactive elements—like radioactive carbon, for example—to date rocks that are millions or billions of years old.

- Radiometric dating depends on a very simple principal: All rocks contain small amounts of naturally radioactive elements, and these radioactive elements have different isotopes within them.

- Isotopes are variations of the same element that have different numbers of neutrons in their nucleus; some isotopes are unstable, and some are stable. The unstable ones decay to stable ones at a fixed rate, which we call the half-life of that isotope.

- You can measure the ratio of the original unstable isotope to what we call the daughter isotope, the one that it is decayed down to, and then you can determine how many half-lives have gone by to determine the age of the rock.

- Through the 1940s and 1950s, whenever volcanic rocks were found on the sea floor, they were found to be surprisingly young—less than about 200 million years old (only 4% of the age of Earth).

- If the entire ocean floor is 200 million years old or younger, and the continents are actually much older, then there is something wrong with the idea that the ocean floor is the oldest, deepest, and coldest part of Earth, which was the understanding up until this point.

- Drilling in the Atlantic Ocean proved that the sea floor was made of basaltic lava—a particular kind of volcanic lava rock—and that the ages were all less than 200 million years. The key finding was that the ages progressively got older when moving away from the mid-ocean ridges.

- Basaltic lava composes 50% of the surface of Earth; it is about the most common bedrock type on the whole planet. Basaltic lava is what we call a mafic rock that has erupted by coming out of magma that came directly from Earth's mantle.

- Once magnetic information and radiometric dating from lava rocks were combined, oceanographers were not only able to determine the age of rocks at a particular place, but they were also able to map out the entire ocean floor all over the planet.

- From this data, the age of the ocean floor proved all over the world to be as young as was initially surmised—less than 200 million years. Additionally, the age of the ocean floor is, in fact, symmetrical about the mid-ocean ridges.

- The difference in the thickness of magnetic stripes in a map of the age of the ocean floor is a direct measure of how rapidly the ocean floor has been spreading. This information shows that the East Pacific Rise is spreading much more quickly than the Mid-Atlantic Ridge.

- The rate of seafloor spreading can be calculated from the widths of stripes on the ocean floor, and it gives us a sense for how rapidly tectonic plates move.

- The rate of seafloor spreading is actually pretty slow. It is measured on the scale of a few centimeters to a maximum of about 20 centimeters per year of creation of new crust on the planet.

- If the Atlantic Ocean really was closed up about 180 to 190 million years ago, then instead of an ocean, there was a seamless continent that included North America, most of Europe, Africa, and South America that was later subjected to continental drifting.

Continental Composition

- Continents are made of rocks that are different from the dense basaltic lava rocks of the sea floor. In fact, they are made of the least dense of the common rock types, and they accumulated as Earth's interior convection proceeded.

- Continents are 40 to 80 kilometers in thickness and are the material that was least dense and, therefore, rose to the surface of Earth—in a process called **continental rifting**.

- In the process of continental rifting, continental domes form from the heat of magma beneath the crust. Faults develop as the crust begins to break up. Strong volcanic activity begins and continues, forming a central rift valley.

- Keystone blocks, blocks of crust that look like books sliding on a shelf when composing, form as faulting continues. Activity continues, and true oceanic crust forms as the continent completely separates.

- The geologic makeup of the oceanic crust is entirely different from the makeup of continents; the dense oceanic crust is thinner than continental crust, and it is heavier, so it rides lower in Earth's somewhat fluid upper mantle.

- The heat at mid-ocean ridges drives a chemical engine involving vast amounts of seawater that alters the rocks and provides the energy for **hydrothermal vents**.

- These vents are called **black smokers** because they look like industrial-aged chimneys pouring out black smoke (which is actually superheated water) into the seawater at the bottom of the ocean.

- The energy from black smokers drives the deep-sea vent communities and the chemosynthesis we will explore later when we look at the energy balance of life on the planet. Ultimately, it is also the source of many of our deposits of copper, iron, nickel, and even gold.

Important Terms

black smoker: One type of hydrothermal vent in which the hot-water plume is laden with mineral particles that give it the appearance of smoke.

continental drift: The early 20th-century theory that the continents had moved with respect to one another over Earth's surface through geologic time; this theory is now superseded by the theory of plate tectonics.

continental rifting: The breaking up of a continent along a narrow zone of faulting and volcanism as a beginning stage of new mid-ocean ridge formation.

hydrothermal vent: A seafloor hot spring where superheated, chemically laden water is discharged from the oceanic crust.

magnetometer: A device that measures the strength and orientation of Earth's magnetic field.

Panthalassa: The single large ocean hypothesized by Alfred Wegener that surrounded Pangaea, the unified single continent that has since rifted apart.

Suggested Reading

Cone, *Fire under the Sea*.

Oreskes, *Plate Tectonics*.

Questions to Consider

1. Can you think of other scientific theories besides plate tectonics that rapidly developed when new evidence of a wide range of very different types became available at the same time?

2. What does it mean for a scientific theory to be accepted? Can it ever be said to be proven?

The Plunging Sea Floor and Deep-Sea Trenches

Lecture 7

Ocean-floor crust is created at ridges, so it must be consumed elsewhere: Subduction zones at deep-sea trenches are the locations where ocean floor is recycled back into Earth's mantle, and transform faults link up the ridges and trenches, completing the plate tectonic system. Subduction zones are the sites of the greatest earthquakes and tsunami. Oceanic trenches as deep as 11,000 meters are the product of plate subduction. The plate tectonic cycle is one of constant destruction, renewal, and reconfiguration of the ocean basins, but the continents remain mostly intact.

Subduction Zones at Deep-Sea Trenches

- If ocean-floor crust is created at ridges, does that mean that the planet keeps getting bigger—like an inflating balloon? In the mid-1960s, the evidence for seafloor spreading had become clear. The scientific community had accepted it, and the expanding Earth theory had supported it.

- For seafloor spreading to occur, Earth would actually have to gain new mass somehow, and there are no new sources of mass. In addition, Earth has stayed exactly the same size over time.

- All of the ocean floor that is being created at mid-ocean ridges must be consumed elsewhere in exactly equal amounts to keep everything the same on the planet—except for this cycle of creation and destruction of the ocean floor or of plates.

- At deep-ocean trenches, there are places called **subduction zones**. Harry Hess recognized these in 1960 when he talked about the formation of crust at mid-ocean ridges but also of the destruction of crust by disappearing down the deep-ocean trenches—for which there is geological and seismological evidence.



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A great example of a hotspot is the Hawaiian Islands, including the Emperor Seamounts, which extend away from Hawaii in a northwestern line across the Pacific Ocean over thousands of kilometers.

- Deep-ocean trenches are the locations where the ocean floor is recycled deep back inside Earth's mantle. The ocean trenches are long and relatively narrow, but they are not very wide.

- The *Challenger* expedition discovered ocean trenches, which get up to 11,000 meters deep—almost 3 times as deep as the average depth of the ocean. Most of ocean trenches encircle the Pacific Ocean.

- Subduction zones are sites where the ocean floor is plunging into the mantle. These zones are places where the crust of the ocean floor is carried below the continent or, in fact, sometimes carried below another piece of oceanic plate.

- Subduction zones are association with very specific features: There are deep-ocean trenches in the sea floor, and behind them are a series of volcanoes that either are associated with volcanic islands in the ocean or are volcanoes that are on land that parallel the deep-ocean trenches.

Earthquakes and Tsunami

- Putting the puzzle of subduction zones together required looking at earthquakes and seismological data. In the late 19th century, seismometers were developed that locate earthquakes.

- Up into around the 1930s, various seismologists were making maps of all of the earthquakes around the globe, and what they found—and what has been confirmed since then—is that earthquakes do not occur in random locations on the planet. Instead, they occur in very specific places.

- If you look at a map of all the earthquakes that have occurred above a certain threshold of magnitude, almost all of them occur in the belts that are between the deep-ocean trenches and the volcanoes.

- When the depths of the earthquakes' foci—the origin points of the earthquakes—are plotted, they make a progression from the shallow earthquakes of the trench to deeper and deeper earthquakes moving away from the trench going down.

- This was recognized in the mid-1930s by 2 different seismologists, Kiyoo Wadati in Japan and Hugo Benioff in California. These **Wadati-Benioff zones** are the belts of earthquakes that plunge their way down into Earth.

- In the 1960s, as the plate tectonics story was coming together, these zones were further recognized as the signature of the destruction of the oceanic plate that was created at a ridge and has gone down a subduction zone, ultimately to be reincorporated into Earth's mantle.

- Most earthquakes occur in the upper 20 kilometers of Earth; we call them shallow earthquakes. In these Wadati-Benioff zones near the trenches, however, earthquakes can progress as deep as 660 kilometers into Earth.

- Subduction zones are, tectonically speaking, the most dynamic environment on the planet. One of the dramatic manifestations of subduction zones are the great subduction earthquakes that create the biggest tsunami on the planet.

- On December 26, 2004, a magnitude 9.1 earthquake off the coast of Indonesia created the tsunami that devastatingly killed so many people. In 2011, another very large subduction zone earthquake created the tsunami that devastated northern Japan.

- Tsunami occur as a result of the plate motion at subduction zones, and we call them convergent margins because they are the boundaries between 2 plates where one plate is converging on the other plate, carrying it down, and the plates stick together for a period of hundreds or thousands of years and then pop forward in an earthquake.

- Subduction zones cause the largest earthquakes on the planet. These zones are where most of the seismic energy is released and where the plate tectonic motions are both the most dramatic and the most devastating.

Types of Plate Boundaries

- Continental rift zones are places where new oceanic crust is created and then moves away from the mid-ocean ridges, progressively getting older with age as its center spreads.

- Continental rift zones are called divergent plate boundaries because the plates are moving apart and new surface of Earth is being created. They all begin as continental rifts and develop into ocean basins.

- On the other hand, subduction zones—associated with deep-sea trenches, earthquakes, tsunami, and arc volcanoes—are called convergent plate boundaries because the oceanic plate that has been created at mid-ocean ridges is being destroyed and ultimately recycled into the interior of Earth.

- Collision zones exist when the plates that have continental crust on them collide with one another at convergent plate boundaries. These are the sources of some of the largest mountain ranges on Earth.

- Divergent plates and convergent plates are linked by a transform plate boundary also known as a strike-slip fault. The difference between a transform boundary and the other plate boundaries is that the oceanic crust—or, in fact, any part of Earth's surface plate—is neither created nor destroyed; the plates are simply moving side by side relative to one another.

- These **transform faults** are accommodations of all of the geometric irregularities of the plates on the surface of Earth, and they link up the ridges and the subduction zones—completing the plate tectonic system.

- An oceanic **fracture zone** is kind of a dead fault or a fossil fault. It no longer has the lateral movement because it is not between 2 ridge segments; it is off to one side of both of the ridge segments.



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One of the dramatic manifestations of subduction zones are the great subduction earthquakes that create the biggest tsunami on the planet.

- Transform faults were very important in developing the theory of plate tectonics because they are a trace of how the plate motions have taken place, so they show the direction the plate has been moving over the history of that plate.

Volcanic Activity: Seamounts

- Another aspect of the bedrock geology of the sea floor is the innumerable, seamounts and islands that have formed through volcanic processes on the ocean floor.

- For the most part, seamounts form as volcanoes in 2 key settings in the ocean. The first setting is at the mid-ocean ridges. At these locations, volcanism is occurring, so there is a lot of upwelling of lava along the riffs, which sometimes concentrates into a particular zone and builds up a volcanic edifice—a volcanic mountain or island—if it extends above sea level.

- As the plates separate and move away from a mid-ocean ridge, they cool and subside through that cooling and densification so that the sea floor gets deeper and deeper.

- As the plates carry these now-extinct volcanoes away from the ridge once they get away from the source of magma that fed the lava, then those volcanoes perhaps start as islands and subside to become seamounts. This is the way that most seamounts are formed.

- A specific type of seamount was recognized and named by Harry Hess: a seamount that has the shape of a mesa, or tabletop, with a high ridge but a very flat top. Hess gave these special table mounts the name **guyots**.

- A second type of seamount called a hotspot forms at a source of volcanic energy—a source of lava and hot magma from Earth's mantle—that sits in a particular place with a plate moving over the top of it. A great example of a hotspot today is the Hawaiian Islands.

- At the time that plate tectonics was being accepted, hotspots were recognized as having formed from a stationary source of new magma in the mantle, a reservoir in Earth's mantle called a mantle plume.

- In a mantle plume, the upwelling added extra heat that would create a volcano. Then, the plate shifted over the top of that, creating another volcano. The plate repeatedly shifted to create more and more volcanoes. This repetition creates a track line that shows how a plate has moved, assuming that the hotspots have remained stationary over time.

- Recent research has shown, however, that hotspots can move in the mantle. Over a short geological timeframe, though, hotspots are predominantly stationary.

Plate Tectonics

- Tectonic plates are not plates of Earth's crust, the ocean crust, or the continental crust. There is something much thicker and more rigid that includes a big portion of the upper mantle of Earth as well as the crust that overlies it called the **lithosphere**.

- Below the lithosphere is a region called the **asthenosphere**, which is less rigid. It is not molten, but it is partially melted enough to flow. Tectonic plates move around on Earth's surface as rigid blocks riding on top of this weaker asthenosphere—the flowing part of the mantle.

- Convection due to heat in the interior of Earth is the primary driving mechanism for these plate motions on the surface. Convection, in turn, is driven by the subduction side of the cycle, the downwelling of the surface of Earth.

- Ideas of continental drift have been around for hundreds of years, but even after being developed in a coherent way in the 1920s, these ideas were not accepted by the scientific community until all of this evidence came together.

- Then, in the 1960s, there was a total revelation in understanding Earth science and how the oceanic crust formed. Plate tectonics was not just beginning to be accepted, but it actually became the dominant paradigm for Earth sciences as a whole.

Important Terms

asthenosphere: The slow-flowing portion of Earth's mantle on which the rigid plates of lithosphere float and move.

fracture zone: The inactive trace of a past transform fault beyond the overlap of offset ridges; they may extend thousands of kilometers across the ocean floor.

guyot: A characteristically flat-topped seamount that was once eroded by wave action as an island and is now entirely submerged.

lithosphere: The rigid outer portion of Earth's crust and uppermost mantle that makes up the tectonic plates.

subduction zone: Location where oceanic plate lithosphere (the sea floor and its underpinnings) descend into Earth's mantle, consuming the tectonic plate.

transform fault: Location where one plate slides past another on Earth's surface—neither creating nor consuming plate area—especially those between offset spreading ridge segments.

Wadati-Benioff zone: The planes of earthquakes extending deep into Earth that mark the location of the consumed plate slab from subduction.

Suggested Reading

Garrison, *Essentials of Oceanography*, chap. 3.

Menard, *The Ocean of Truth*.

Questions to Consider

1. What do you suppose happens to a subducted oceanic plate once it sinks back into Earth's deep mantle?

2. Why do most earthquakes take place under the sea rather than on the land?

The Formation of the Earth and Its Ocean

Lecture 8

As the Solar System formed, Earth uniquely had the right conditions and ingredients for liquid water on the surface, and it has had an ocean for 4 billion years. Water was present from the initial accretion of the planet and separated from rock early in Earth's history; comets may have added more water was well. The early Earth was too hot for oceans to form, but gradual cooling took place through 25 million years of steady rain. The Moon formed through collision of a Mars-sized body with the early Earth.

The Origins of Earth

- Earth's ocean is an essential component of the development of Earth as a planet itself, and it has been a defining feature since very early in Earth's history.

- Earth began, as cosmologists tell us, as a result of the big bang that occurred 13.7 billion years ago; the universe has been expanding ever since.

- Initially, the big bang was this singularity where all of the energy and potential matter in the universe was concentrated, and as it exploded and expanded, an unimaginable amount of energy started out as a wave, an electromagnetic radiation, propagating the opening space.

- After about 1 million years, that energy started to cool down enough to turn into atoms, the building blocks of matter. Initially, it was basically all hydrogen, the simplest possible atom.

- After another billion years, matter was not absolutely uniformly distributed, so gravity started to act, causing any matter that was in a region to start to clump together into the first stars. In fact, those stars in big clumps formed the first galaxies.

- The stars then had enough gravity to collapse because the densification caused higher and higher temperatures in the interior of those stars, creating the heavier elements.

- Through the process of nuclear fusion, the innumerable stars that formed the innumerable galaxies across the universe started synthesizing the heavier elements that make up the basic building blocks of most of matter—such as carbon, oxygen, nitrogen, and some of the metals.

- Some of those stars were so large and had so much energy through the nuclear fusion process that they would explode and form supernovas, which would build even more heavy elements through nuclear fusion but also blow them up and spread them throughout this early universe.

- All of the elements on the periodic table were formed through the process of supernova formation, with the most abundant elements being the relatively light ones and the heavier ones being rarer.

- As this process continues, galaxies, stars, dust, and gas are built up and are held together by rotation and gravity because of some of the original captured momentum from material flying up from the big bang and from the supernovas driving the rotation of different galaxies.

- The universe has an estimate of perhaps 50 billion galaxies, each one holding something on the order of 50 billion stars.

The Formation of Our Solar System

- Our Sun is a pretty ordinary star. It is in the outer regions of the Milky Way Galaxy—a sort of densely populated suburb. There are many stars around, but even a densely populated part of space is actually pretty sparse.

- The Sun formed through the condensation of the **solar nebula**, which is a large-scale cloud of about 75% hydrogen and 23% helium. The other 2% is all of the other elements that had been made in various stars over billions of years in the early stages of the universe.

- Probably through the process of supernova formation or through the supernova of nearby stars sending out shock waves, the solar nebula was hit by some shock waves and started rotating about its gravitational center.

- As it rotated, the cloud started to turn into not so much of an amorphous cloud but a disc. Once it started spinning, there was in the momentum a centrifugal acceleration that counteracted the gravitational acceleration that was pulling it together, causing it to clump down in the opposite direction but flatten out in the plane of the spin.

- This process led to accretion, in which gravity pulled everything together and clumped it all into a protosun, or an early stage of our Sun, that became a factory of nuclear fission and fusion—and planets.

- The vast majority of the matter in our Solar System is located in the Sun itself, but outside the Sun is orbiting matter that differentiated based on temperatures of melting—or of solidification or condensation.

- Close to the protosun, metals exist that have the appropriate melting temperature conditions and densities to get close to the Sun and form metal-rich inner planets like Mercury and Venus.

- Far from the protosun, in the outer reaches of the Solar System, the lowest-temperature compounds condense, forming gas-rich outer planets—also called the gas giants—like Jupiter, Saturn, and Uranus.

- In between the gas giants and the metal-rich inner planets, conditions were right to condense large amounts of matter that have intermediate densities like silicon, magnesium, and water—a combination of hydrogen and oxygen atoms. Earth and Mars have these features.

- At this time, about 4.56 billion years ago, a bunch of orbiting lumps of rock existed—think of them as asteroid-sized pieces—called **planetesimals**, which were growing and clumping as their gravity swept up dust.

- By this period, these planetesimals swept together into a planet-sized mass of proto-Earth that had a mass of 80–90% of the present-day Earth.

- It turns out, the date of 4.56 billion years ago is known with a precision of about a million years—a precision of fractions of a tenth of a percent—because we can date the meteorites that arrive on Earth, which are little bits of planetesimals that formed with the Solar System but did not actually get incorporated into a planet.

- When these planetesimals were arriving on the planet and bringing their momentum, the planet was increasing in size and was collapsing under its own weight.

Earth's Stratification

- Around 4.56 billion years ago, the young Earth went through a total melting process over a period of about 100 million years. As partial melting began, Earth differentiated again through a process called **density stratification**, in which the heavy metals—primarily iron and nickel—sunk toward the center and formed Earth's core.

- Today, the core of Earth is a gigantic ball of mostly iron that is differentiated into an inner core, which is solid due to the pressure conditions there, and an outer core, which is liquid iron. Earth's core takes up about 1/3 of the planet.

- While the core of Earth was forming, the lighter elements were separating from the heavier elements and were moving toward the outer part of Earth to form the crust, which is very thin and composes a small percentage of Earth, and the mantle, which takes up about 2/3 of the planet.

- During this process, silicon, aluminum, and magnesium all bonded with oxygen in various ways to form all of the rock compounds found on the planet.

Earth's Moon

- Compared to other planets, our satellite—the Moon—is quite a large proportion to the size of our planet. The formation of the Moon has been a topic of speculation and research over time.

- The best calculations of physicists suggest that the Moon formed through the collision of a Mars-sized planetary body and early Earth.

- This cataclysmic collision probably blew up and remelted much of the Earth that had initially formed through density stratification. The Mars-sized planetary body merged partly with Earth's core and ended up separating from Earth to then orbit Earth, leaving Earth to resolidify again.

Earth's Atmosphere

- It appears that the solid surface of Earth had formed and had largely cooled by 4.56 billion years ago. Earth would have had an original atmosphere that was made up of mostly hydrogen and helium gases, which were left over from the formation of the Solar System.



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Volcanic outgassing occurs as a result of every volcanic eruption and includes a release of such gases as hydrogen, nitrogen, oxygen, and carbon dioxide.

- This atmosphere of hydrogen and helium was very light and easily escaped Earth's gravity and solar radiation. It is probable that this original atmosphere was beginning to form but never really became the atmosphere of Earth because it was blown away by solar wind, an inflow of particles that are accelerated by the outer region of the Sun.

- The **volcanic outgassing** of volatile substances (as a result of volcanic eruptions) from inside Earth produced the second atmosphere, which was principally composed of carbon dioxide and water vapor. It is possible that comets added significant amounts of water as well.

- By about 4.56 billion years ago, Earth had an atmosphere that was heavy in water vapor, but the surface was still too hot for liquid water to condense, so an intense shroud of clouds formed that completely blocked out the sunlight down to the surface.

- Most likely, these conditions led to an intense rain that lasted for 25 million years. Simulations suggest that the hot surface would evaporate the rain as soon as it fell, maintaining the cloud shroud around Earth and cycling rainfall down to the surface.

- As a result, there existed a phenomenally efficient and active convection system that drew heat out of Earth and sent it out toward space through that evaporation-and-rainfall cycle. The 25 million years of rain cooled the surface of Earth enough to form the crust it has today.

The Origin of the Ocean

- Through gradual cooling of the surface of Earth, liquid water began to accumulate. The surface cooled down enough to form pools, then bigger pools, and then lakes and bodies of water in low spots on Earth. This began a process of dissolution of minerals in which the water started to dissolve some of the minerals on the surface of Earth.

- In addition, this process began the rock weathering cycle, which broke down the minerals so that the water started to gain some salinity.

- Some recent studies suggest that an ocean—a liquid water surface—may have completely covered Earth's surface by about 4 billion years ago. The reason this is a possibility is the Sun at that time was probably faint and therefore put out less heat than it does today, which meant less evaporation.

- In addition, the ocean may have been completely covered with ice to a depth of about 300 meters with liquid water below. The early Earth was cooled enough at this point to begin the process of condensation.

- All the geological evidence scientists have analyzed suggests that Earth has had a large-volume, liquid-water ocean continuously since very early in its history—for at least 4 billion years.

- In that entire length of time, Earth's ocean has neither frozen solid (though it may have frozen over) nor boiled away.

- Plate tectonics probably also started early, differentiating the crust into continents and ocean basins before 4 billion years ago.

Important Terms

density stratification: The process by which the early Earth separated into concentric layers with denser iron-rich material sinking to form the core and lighter elements and rock compounds forming the mantle and crust.

planetesimals: Small asteroid-like clumps of rock orbiting around an early Sun that accreted together by gravity to form Earth and other rocky planets.

solar nebula: The rotating cloud of gases and particles from which the Solar System formed.

volcanic outgassing: The release of water, carbon dioxide, nitrogen, and other gases from Earth's interior at volcanoes.

Suggested Reading

Emiliani, *Planet Earth*.

Garrison, *Essentials of Oceanography*, chap. 1.

Questions to Consider

1. What might be the implications for life on Earth of the fact that the oceans have been present in liquid form throughout essentially all of Earth's time?

2. We saw in the previous lecture that the ocean basins are very young geologically, but now we know that the water is very old. How are these facts consistent with one another?

The Early Ocean and the Origins of Life

Lecture 9

Over the first 2/3 of Earth's history, the ocean, atmosphere, and rocky surface changed from an early oxygen-poor state to the present oxygen-rich system, and the development of life and photosynthesis dominated these changes. Early atmosphere had no oxygen but gradually changed to its present composition due to photosynthesis in the ocean. Liquid water is the most essential ingredient for life on Earth; the ocean provided the only stable environment over the eons of early evolution.

Earth's Third Atmosphere

- The early Earth's atmosphere had essentially no oxygen in it, and that is the missing ingredient from the composition of Earth's second atmosphere.
- The evolution to the present composition of the atmosphere that does include a significant proportion of oxygen is the evolution to the third atmosphere.
- Detectable changes in the chemistry of the oldest rocks on the planet show that the initial rocks and the initial water started to interact about 3.5 billion years ago.
- At that time, the composition of the atmosphere started to gradually change. At first, carbon dioxide was dissolving in water, forming carbonic acids, which in turn dissolved more rock.
- About 2 billion years ago, the **oxygen revolution** began. The atmosphere, which had been completely lacking in free oxygen up to that point, suddenly became rich in oxygen. We know about this from the chemistry of rocks.

- The oxygen revolution on the planet was caused by the development of photosynthesis, in which organisms used sunlight and carbon dioxide to make oxygen in the atmosphere.

The Process of Photosynthesis

- **Photosynthesis** is a process in which carbon dioxide and water are turned into food or fuel, which essentially takes the form of simple sugars—glucose and free oxygen. It is the basis of energy for almost all life on Earth today.

- Photosynthesis requires a set of very detailed reactions that are catalyzed by and mediated by a molecule called chlorophyll, or other related molecules that are organic compounds that are only created by life on the planet.

- Chlorophyll uses the energy of sunlight to make a chemical reaction occur that would not otherwise occur by inorganic processes. Sunlight is the energy source, and chlorophyll is the catalyst; carbon dioxide and water are turned into sugar and oxygen.

- Sometime in the early stages of the planet, between 3.5 billion and 2 billion years ago, whatever life already existed developed the ability to carry out photosynthesis.

- The oxygen revolution became so dominant on the planet—and, in fact, in the ocean—that between 2 billion years ago up to about 800 million years ago, oxygen went from being essentially nonexistent to composing 20% of the atmosphere.

- The present-day atmosphere has about the same composition as the atmosphere of 800 million years ago: about 80% nitrogen, 20% oxygen, and very small trace amounts of carbon dioxide and other gases.

- This composition of the atmosphere requires ongoing photosynthesis to maintain it, and active maintenance of the third atmosphere is a hallmark of the planetary system.

A Liquid Ocean

- Paleontologists know, from a wealth of information from rocks all over the planet, that there is no evidence for land-based life before about 470 to 500 million years ago.

- Therefore, marine life maintained the atmosphere through the photosynthetic process for most of the past 2 billion years and certainly for the first 3/4 of those 2 billion years.

- This implies that the planet has continuously had a liquid ocean throughout nearly all of Earth's history—at least throughout all of the time since photosynthesis began, which was about 2 billion years ago.

Stability of the Ocean

- The existence of a photosynthetic system has required Earth's temperature to stay within a very narrow band for several billion years. The surface temperature of Earth has stayed between 0°C and 100°C on average—over the volume of the ocean—for all of that time.

- **Geochemistry**, the chemistry of rocks, throughout all of the eons of geological history also shows that the ocean has had a composition that is fairly similar to the present day for at least about the past 600 million years—and probably much longer.

- It is a little less certain, but it is most likely that the total volume of the ocean has not changed all that much over the span of life on Earth either.

- The ocean's basins are recycled through the plate tectonic cycle, but the ocean itself is not; the ocean is far older than its container.

The Origin of Life

- Before there was an oxygen revolution, there was life on the planet. That life was probably a fairly simple kind of life; single-celled organisms dominated, and we can assume that these organisms were not photosynthetic.

- All life on Earth requires liquid water because water is a fantastic solvent; in fact, it is often called the universal solvent.

- In addition, water has a phenomenal property of retaining heat and moderating temperature, so it is important for organisms to manage the heat within their structures.

- Water also can suspend solids, so it can suspend wastes and nutrients and allow you to expel them from your cellular structure.

The Origin of Organic Molecules

- It is possible that the basic building blocks of life—basic organic compounds—could have originated in space and could have been transported to Earth by comets, asteroids, and meteorites.

- However, it is also possible for organic molecules to have formed through inorganic processes—processes that have nothing to do with life—and to have been spontaneously created on Earth through basic chemistry.

- In 1953, Stanley Miller and Harold Urey performed a famous experiment—now known as the **Miller-Urey Experiment**—to test the question of whether organic molecules, carbon-containing compounds, could be made spontaneously on Earth.

- In this experiment, Miller and Urey boiled some water to make water vapor inside a sterilized and evacuated vacuum tube and injected into the tube a mixture of inorganic gases, which they thought represented the gas composition of Earth's early atmosphere: methane, ammonia, hydrogen, and water vapor.

- Miller and Urey then ran the gas mixture into a chamber, where they added a sparking system to simulate lightning. They ran this spark plug for multiple days, sparking the material, and then they condensed the gas back to a fluid and sampled the water droplets.

- As a result of this experiment, the water contained organic compounds—amino acids, simple sugars, and some proteins—that had not been present in what had been added to the system. The chemical building blocks that would need to be present to assemble life were created.

- Further experiments have shown that you do not even need the spark; you just need some source of energy, which can be in the form of heat coming from a chemical reaction or from a hot spring, for example.

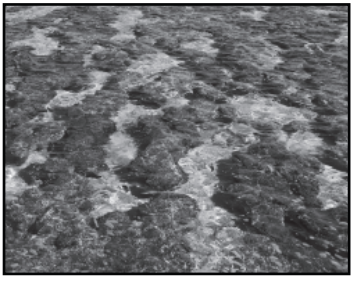
Where Did Life on Earth Begin?

- Based on research about organic compounds forming from inorganic compounds, it is possible that life could have begun on the planet as opposed to being transported here from space.

- Life on Earth had to begin in the ocean because for 3/4 of the time that we know about, there has only been life in the water and not on land.

- Perhaps in the open ocean area, the pelagic photic zone or the pelagic deepwater zone, the building blocks of early life could have been assembled.

- Perhaps life formed in shallow tide pools or lagoons in regions around the coastline where there was shallow water and a potential for lightning to strike that water or for heat in the form of ultraviolet energy to come from the Sun.



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The oxygen revolution might have been carried out by organisms much like stromatolites, which are mats of colonial cyanobacteria.

- Charles Darwin suggested that he imagined that, in some warm little pond somewhere, the basic ingredients for life were assembled and a strike of lightning or something else sparked life into existence.

- Another option would be that life began in a place where we see it today being completely separate from the photosynthetic system on Earth: in the deep-sea hot springs, where the black smoker vents are found.

- Each of these theories has pros and cons. The open-ocean idea has almost entirely been rejected because any spontaneously created amino acids would be diluted and widely distributed in the great volume of the water, so there wouldn't be a high enough concentration of these organic compounds in any one place.

- The shallow tide pools or lagoons are definitely a possibility. However, ultraviolet radiation from the Sun is damaging to the delicate carbon-chain compounds that life depends on.

- Many of the people who study early life forms think that it is not at all unlikely that the deep-sea hot springs are places for life to have initially evolved. One of the reasons is that there is a continuous supply of energy—chemical and heat—for life to exploit in those areas.

- A second advantage of the deep-sea hot-spring setting is that it is deep in the ocean floor, so it would be a refuge for early life that could prevail through cataclysmic events that were occurring on the surface of the planet, such as the bombardment of asteroids.

Early Life

- Early life was certainly composed of single-celled organisms, and it was similar to what we call prokaryotes today. The earliest life eventually branched into the 3 fundamental domains of life that we have today.

- Eukarya is a domain that includes all of the organisms with complex cellular structure and a nucleus. The 2 domains of life that have cells but lack a nucleus and any kind of complex internal structure are Bacteria and Archaea.

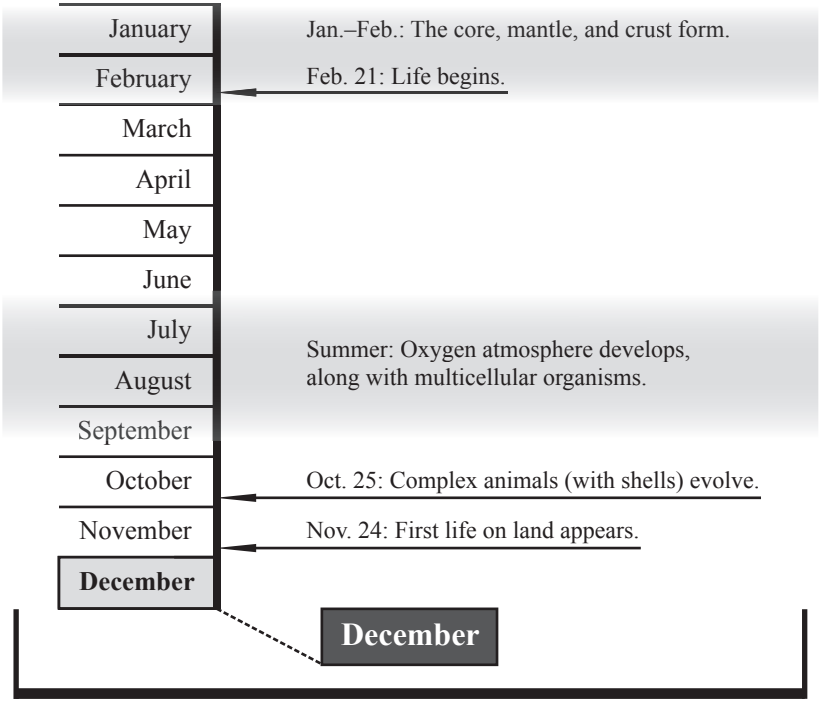
- A 3.5-billion-year-old fossil microorganism in a rock formation called the Apex Chert, which is in Australia, is a fossil of something that was produced by a living organism.

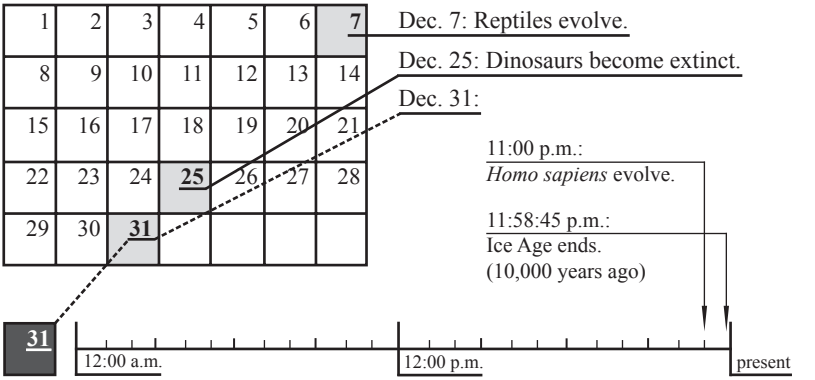
- The existence of this organism suggests that there were some fairly complex structures at that time. Therefore, life is probably even older than that fossil and probably began sometime close to the time the ocean formed.

- By the time of the oxygen revolution—between 2 billion years and 800 million years ago—there were great numbers of **cyanobacteria**, which were early photosynthesizers.

- The oxygen revolution might have been carried out by fossil stromatolites, which were fossil mats of colonial cyanobacteria. Stromatolites are still present today, in much the same form, in Australia as well as in other places around the world.

4.6 Billion Years Compressed into 1 Year





Important Terms

cyanobacteria: The single-celled organisms that carry out photosynthesis; likely the agents of the oxygen revolution.

geochemistry: The science that studies the chemical composition of rocks as a clue to past conditions or geologic processes.

Miller-Urey Experiment: A 1955 laboratory study that demonstrated that organic compounds could be spontaneously generated from inorganic carbon compounds and energy.

oxygen revolution: The wholesale modification of Earth's atmosphere from an oxygen-poor one to the present oxygen-rich one between 3.5 and 0.8 billion years ago.

photosynthesis: The biological process of capturing solar energy by using it to make carbohydrates as food.

Suggested Reading

Broecker, *How to Build a Habitable Planet*.

Fry, *The Emergence of Life on Earth*.

Questions to Consider

1. What environment or habitat in the ocean might have been the most stable and unchanging for early life to evolve in?

2. An activity for the ambitious: Instead of all of Earth's geologic history represented as a single year, try laying it out as a length—perhaps in your living room or backyard. Scale it to 10 feet equals 1 billion years, or whatever fits in the space. How far along the line are all of human history and all life on land?

Marine Sediments—Archives of the Ocean

Lecture 10

After the ocean floor was created, sediments accumulated on it in layers that can be interpreted into a history of the ocean and climate through time. Marine sediments preserve clues to the environment at the time of their deposition in the types of fossils, the nature of grains of sand, and the chemical fingerprints of past climate. Many of the rock formations we see on land began as marine sediments and were incorporated into the continents through plate tectonic processes.

Sediments on the Ocean Floor

- Sediments were continuously accumulating in the ocean as soon as the ocean floor was created. They accumulate on the ocean floor in layers that can reach great thicknesses. In fact, they are like tree rings that can be "read" as a history of the ocean and climate through time as they are deposited.

- **Sediments** are particles of inorganic or organic matter that can accumulate in some loose and unconsolidated form in the ocean. These particles originate from the erosion of rocks, volcanic eruptions, chemical precipitation, living organisms, and from space.

- Because they are laid down sequentially, sediments provide a record of the organisms, physical and chemical processes, and atmospheric and climatic conditions that existed at the time the sediments were formed.

- We have a 190-million-year sedimentary record in the oceans and a 4-billion-year history in sedimentary rocks now preserved on the continents.



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Mount Everest in the Himalayas is the highest point on the entire planet at 8,800 meters above sea level. Marine rocks found at the top offer a history of the plate-tectonic events that got them there.

- Sediments provide a record of events in Earth's history. The dinosaurs were present on Earth through the Mesozoic Era up to the end of the Cretaceous Period, and at that time—about 65 million years ago—it is most likely that a massive asteroid struck Earth in the region that is now the Yucatan Peninsula and Gulf of Mexico.

- The asteroid sent up an incredible amount of material from the impact into the atmosphere that blacked out the Sun, changed the climate on the planet, caused a cataclysmic tsunami through the Gulf of Mexico region, and fundamentally changed the history of life on this planet.

- Sedimentary rocks provide a direct record of that impact. The Ocean Drilling Project obtained a core sample taken by the scientific ocean drilling vessel *JOIDES Resolution* that preserves a record of before, after, and during that event in the sediments.

- Sediments also tell us about the history of plate tectonics and about the history of the continents themselves. Marine sedimentary rocks at the highest altitudes on Earth—including on top of Mount Everest in the Himalayas, 8800 meters above sea level—give us a history of the plate-tectonic events that led them to be found at those heights.

Table 10.1: Classification of Marine Sediment by Sources

Sediment Type	Source	Examples	Percent of ocean floor covered
Terrigenous	Erosion of land, volcanic eruptions, windblown dust	Quartz beach sand, estuarine muds and silts	~45%
Biogenous	Organic—hard parts of marine organisms	Calcareous and siliceous oozes	~55%
Hydrogenous (chemical)	Precipitation of minerals from seawater	Manganese nodules, phosphorites	< 1%
Cosmogenous	Extraterrestrial meteorites and dust	Tektites (glassy spheres), magnetic spherules	0%

Sediment Distribution

- Sediments have many different origins, but they are distributed very unevenly in the ocean. The majority of sediments are present on the continental margins, where the terrigenous sediment is very dominant.

- The continental margins represent only about 22% of the area of the ocean floor, but they represent 87% of all of the sediments in the ocean. The vast majority of sediments in the ocean are concentrated into the small areas that surround the continents.

- An isopach map shows the thickness of accumulations of sediments in different areas around the world.

- By contrast, the deep-ocean floor—the abyssal plains and the ridges—represent 78% of the area of the ocean, but they represent only about 23% of the sediments.

- We have large areas of the ocean floor that are blanketed by sediment, but it is not very thick; the accumulation of those sediments is continuous, but it does not amount to much material because it is a slow process.

Types of Sediment

- Neritic sediments—just as the neritic environment of the ocean is the region that is close to the coastline—are sediments that are sourced directly from the land. Neritic sediments are typically terrigenous and often dominate the sedimentation of the continental margin.

- By contrast, pelagic sediments are sediments that originate in the open ocean. They are mixed of types: Some of them come from the land and are terrigenous, but they are often dominated by biogenous **oozes** on the deep-sea floor. They can occur anywhere in the ocean as well as on the continental slopes, rises, and shelves.

Terrigenous Sediment

- **Terrigenous sediment** is sediment that originates on continents or islands through the erosion of older rocks and from volcanic eruptions. Quartz, feldspar, and clays are the main mineral constituents.

- Every year, 15 billion metric tons of terrigenous sediment makes it to the ocean by rivers, deltas, and streams, for example.

- As sediment makes it into the water, it spreads out onto the continental shelf, making it to the shelf edge and to the region where the **submarine canyons** of the continental slope are present.

- Sediments collect at the upper ends of these submarine canyons and where the slope becomes steeper, bringing the ocean floor all the way down toward the abyssal plains.

- These sediments can flow down these submarine canyons in **turbidity currents**, which occur when there is a bunch of loose and porous sedimentary material stirred up by especially large wave action, resulting in a dense slurry of water and sediment that forms a turbid mixture of water.

- Turbidity currents erode the canyons and form a flowing mass of mud, sand, and even gravel that ultimately form deposits called turbidities, which show up in the continental rock record of sedimentary rocks.

- Another form of terrigenous sediment is the direct input of ash from volcanoes, which sometimes produce huge plumes of ash that spread into the stratosphere and then fall down into the ocean.

- These ash deposits form blankets of sediment so distinctive that individual ash beds from very large prehistoric volcanic eruptions can be identified in core samples of sediments from many places in the ocean.

- A final type of terrigenous sediment is the input of windblown dust that comes directly from the land. In a dust storm, for example, the windblown dust that comes off a desert is picked up and carried to high elevations in the atmosphere and then can spread around the world in very fine particles of clay and dust material.

Biogenous Sediment

- **Biogenous sediment**, the remains of living organisms, is second in abundance to terrigenous sediment and primarily comes in 2 forms: siliceous (silica, SiO_2) or calcareous (carbonate, $CaCO_3$) shells and skeletons of marine animals.

- Some examples of biogenous sediment include coral reefs, calcareous oozes, and siliceous oozes. Corals build very large edifices made of calcium carbonate but also open-ocean, muddy-soft sediments called calcareous oozes or siliceous oozes.

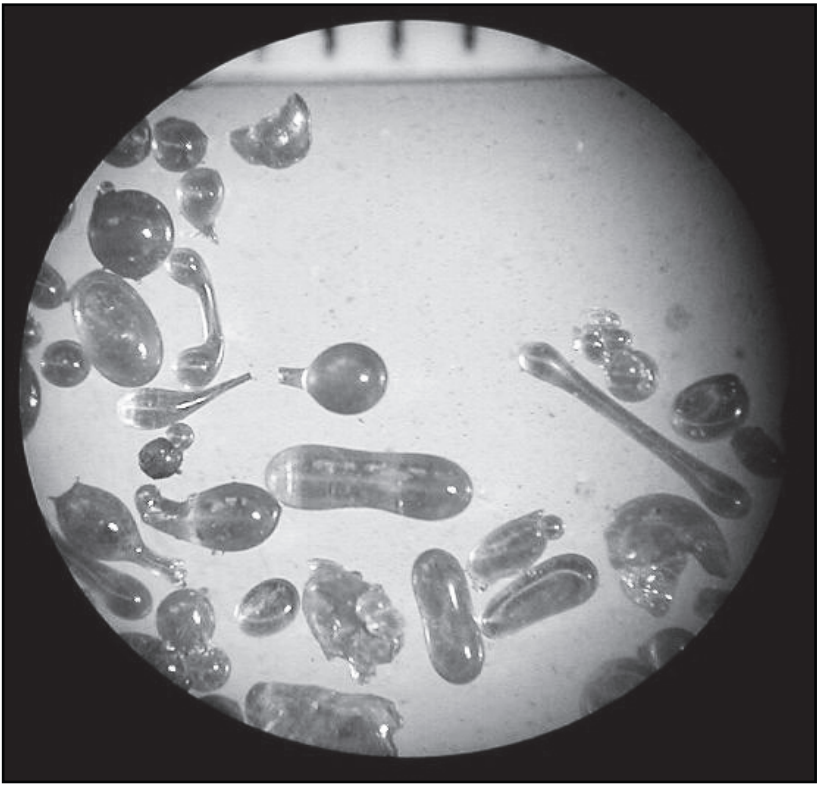
- An organism called foraminiferan is a single-celled amoeba-like organism that makes a calcareous shell and lives by floating as plankton. What's left after it dies falls to the bottom of the ocean to form part of a calcareous ooze. Another organism that contributes to calcareous oozes is coccolithophorid, a calcareous planktonic algae.

- These organisms live in the photic zone, and when they die, they accumulate in certain places of the sea floor. Below a certain depth called the **calcite compensation depth**, which is dependent on oceanographic conditions, they do not deposit because they dissolve before reaching the sea floor.

- What this means is that the open-ocean sea floor has a characteristic stratigraphy, or layering of different types of sediment. The sediment on top of the lava rock is almost typically the calcareous ooze, the carbonate-rich sediments. A siliceous ooze sits on top of the calcareous ooze where the rock has receded below the calcite compensation depth.

- On top of the siliceous ooze—or instead of the siliceous ooze, in parts of the ocean that are not very productive for those particular organisms—exists the red clays, the material that comes in as windblown dust from the land and is the slowest accumulating sediment in the ocean.

- If you look at a map of the world and where sediments exist, you can see some very regular patterns: The continental margins are dominated by terrigenous sediments and the open-ocean floor is dominated by calcareous oozes, but there are places that are unproductive for biology that are dominated by red clays. The siliceous organisms mostly culminate around Antarctica.



Thanks are extended to Michael Daniels for making his microtektite image available to *The Great Courses*.

Microtektites—one of the most interesting forms of extraterrestrial (cosmogenic) sediments—are small glass pellets that look like dumbbells or needles under a microscope.

Chemical (Hydrogenous) Sediment

- **Chemical** (**hydrogenous) sediment** comes from the water itself and include seafloor **manganese nodules**; gypsum, halite, and barite (salt) deposits; and phosphorite nodules.

- All of these hydrogenous sediments form different kinds of compounds and salts that, under the right oceanographic conditions, can be precipitated directly from the water.

- Hydrogenous sediments tend to form on either the continental shelves or platforms or on the floor of the deep-sea abyssal plains in places where other processes—like biological sedimentation or terrigenous sedimentation—are not dominating.

- For example, large parts of the deep-ocean floor have at least some amount of manganese nodule precipitation, which are little cannonball-sized or even golf ball–sized lumps of metalliferous material that is a direct precipitate from the excess manganese, iron, and other metals that are present throughout the water in low concentrations.

- Another example of chemical sedimentation is very small carbonate nodules that are made essentially of limestone. They are also made of calcium carbonate.

- Carbonate nodules are formed in areas of shallow water—especially the banks and platforms associated with coral reefs, lagoons, or atolls—where the water, because of the presence of the corals and other material, becomes supersaturated in carbonate, which precipitates out of the water to form small pellets.

Extraterrestrial (Cosmogenous) Sediment

- One of the most interesting forms of **extraterrestrial** (**cosmogenic) sediment** is microtektites, which are essentially made of glass.

- **Microtektites** are small particles of molten droplets of rock that were ejected into the atmosphere on the impact of an asteroid—like the 65-million-year-old asteroid impact at the end of the Cretaceous Period.

- After being ejected into the atmosphere, microtektites are frozen into a glassy state, fall on the ocean surface, and rain down into sediments. They are never very concentrated, but they are ubiquitous throughout the ocean sediments.

Important Terms

biogenous sediment: Sediment originating as the hard parts of marine organisms.

calcite compensation depth (CCD): Depth below which the water will dissolve calcareous shells such that calcareous ooze does not accumulate as a sediment.

chemical (hydrogenous) sediment: Sediment formed by precipitation of minerals from seawater.

extraterrestrial (cosmogenous) sediment: Sediments with an extraterrestrial origin that fall into the ocean from space as meteorites or dust.

manganese nodule: Roughly spherical particle formed as manganese oxide precipitates from seawater over time.

microtektite: Tiny glassy particles produced by impact melting when an asteroid hits Earth.

ooze: Sediment of the deep-sea floor that primarily originated from accumulated shells and skeletons of plankton; can be calcareous (carbonate-based) or siliceous (silica-based) ooze.

sediment: Particles of inorganic or organic matter that accumulate in a loose, unconsolidated form.

submarine canyon: Any offshore canyon on the continental slope that is formed by erosion due to flows of sediment along the bottom in turbidity currents.

terrigenous sediment: Sediment originating from land that is input into the ocean either by water- or wind-borne transport.

turbidity current: Flow of suspended sediment-laden water down the ocean floor that is driven by density and gravity.

Suggested Reading

Boggs, *Sedimentology and Stratigraphy*.

Hsü, *The Mediterranean Was a Desert*.

Questions to Consider

1. The ocean basins are 200 million years old or less, yet geologists use sedimentary rocks to study ocean environment conditions from a billion years ago or more. Where are the sediments they study, and how did they get there?

2. The finest-sized sediment particles are clay; they can easily remain suspended in the water for long periods of time. What might you surmise this means for the geographic distribution of clay sediment in the ocean as compared to sand?

Offshore Oil and Gas—Resources and Risks

Lecture 11

Marine sediments are the source and host of all oil and gas deposits, the legacy of millions of years of life in the sea. The development of offshore oil brings societal needs and environmental and aesthetic concerns into conflict. The scale of the offshore drilling and production industry is immense, with billions of dollars invested in even a single production platform. Smaller-scale resource extraction from the sea includes minerals, especially salt, and energy extraction through tide generators or thermal energy conversion.

Petroleum and Natural Gas

- There has been an increasing amount of activity, especially in offshore drilling, in regards to oil and gas. It's certainly a very expensive, large industry on the planet, and it's not without risks.

- Petroleum and natural gas are the real drivers and underpinnings of the world's economy because we use the energy that comes from oil and gas to fuel our economy.

- The global demand for oil and gas is not decreasing, despite concerns about the effects of carbon and global warming. Instead, the global demand has been growing by about 2% annually with no sign of any long-term abatement of that demand.

- The United States alone consumes about 25% of the global oil supply, using almost 23 barrels per person per year of petroleum products. The demand in the United States is relatively flat, but the global consumption is rising quickly in other places, such as China.



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Human beings have been drilling oil for about 150 years, and in that amount of time, we've used up about half of all the oil that was laid down over 500 million years into seafloor sediments. The other half, at the current rate, will be tapped in about the next 50 to 100 years.

- For about 150 years, there's been production of oil and production of gas on land. On location, drilling on land is a well-established activity that has involved the discovery of both crude oil and natural gas.

- About 34% of global crude oil and about 30% of natural gas comes from below the ocean floor. This is a $500-billion-per-year activity on the planet, and that activity level is growing today in terms of offshore development of resources.

Sources of Petroleum

- Both on land and offshore, petroleum resources are virtually all hosted and sourced in marine sediments—except for a few natural gas resources that come from lake-bed sediments.

- Oil and gas deposits form in terrigenous and in the neritic sediment environments, which means that they form on the continental shelf and slope—and, especially, on large deltas—in areas where the sediment is being deposited from the land.

- That sediment includes a lot of organic matter, as we'll see, and buries that organic matter relatively rapidly in the subsurface below the sea floor in the sedimentary pile that builds up.

- The biogenous material that covers the bulk of the sea floor—the calcareous and siliceous oozes—is not the source of hydrocarbons in the ocean. The open-ocean floor has a relatively thin accumulation of sediment that is not rich in organic material.

- Deepwater-drilling offshore involves material that is terrigenous sediment—not the open-ocean floor pelagic-style of sedimentation.

Recipe: Home-Brewed Oil

Start with a quiet offshore region where muddy sediments accumulate, rich in organic matter—mostly dead plankton and masses of bacteria. Use anaerobic digestion to break down.

Bury under low-oxygen conditions to 2 km or more at 60–120°C.

Slow cook for millions of years, and voilà!

For methane and other gases, use the same recipe, but bury deeper and cook at 100–200°C.

Source to Reservoir

- Oil is less dense than water. All oils will float on top of water, and natural gas is even less dense than oil, so both of them become trapped in tiny droplets in the pore spaces found in sedimentary rock.

- The lighter oil and gas rises up through the pore spaces in the rock. The water moves down, and the oil and gas move up through density stratification.

- In many places in the world, the oil and gas will move upward through the porous sediments, seep out on the sea floor, and become lost rather than become reservoir accumulations of oil or gas that could be drilled into.

- Sometimes, when geological conditions are right, the oil and gas will rise up until they meet an impermeable layer of **caprock**—like the hot air going up into a balloon and being trapped by the balloon itself.

- The oil and gas rise, forming inverted pools of fluid with the gas on top (underneath the caprock), a layer of pore space filled with oil below the gas, and then a layer below the oil filled with water.

- The permeability of what we call the **reservoir rock** is a fundamental control on whether an oil reservoir is an economically viable accumulation, meaning that if you drilled a well into it, you could suck the oil or gas out into a well. This process requires a relatively permeable rock.

- Marine rocks form the onshore oil fields that we see, but more and more of the newly discoverable oil fields are offshore.

The Offshore Oil Industry

- We all use the products—oil and natural gas—that result from offshore oil drilling but are pretty unaware of the vast technology and effort that goes into obtaining offshore oil.

- Certainly, the oil spill in the Gulf of Mexico in 2010 made everyone much more aware of some of the technologies that are involved, but it's still an industry that's hidden from most of society's view.

- Billions and billions of dollars are spent every year to explore for and develop these petroleum resources in offshore regions—not just in the Gulf of Mexico, but all around the world.

- A typical deepwater exploration well—the kind of well that was being drilled at the time of the Deepwater Horizon explosion—is a phenomenally expensive undertaking: It can cost around $100 million to drill an individual well.

- The technology required to drill a deepwater exploration well is on the cale of effort that NASA uses to get into space because the whole process has to be maintained remotely by robotic systems.

- The offshore oil industry was simply an extension of the onshore oil industry. The first U.S. offshore oil field was developed in southern California in 1915.

- In response to the demand for oil, the industry has moved operations into ever deeper water. In the tidewater regions—what is called the transition zone—or on the shelf, offshore platforms stand on the ocean floor into hundreds of feet of water depth.

- In order for the platforms to stand on the ocean floor, jack-up rigs are floated into place, and then legs are jacked down to the sea floor. These are platforms with very complex foundations, similar to foundations of large buildings and structures on land.

- In deeper water—more than a few hundred feet deep—platforms float and are tethered down with cables. Drill ships and rigs called semisubmersibles are dynamically positioned by large thrusters or large propellers that use modern technology to fix the platform in one location.

- Because of the cost of building these platforms, a single offshore platform drills many different wells. The oil industry has developed directional drilling, or horizontal drilling, technology that allows one platform to drill several wells that reach out in many directions to access portions of a given oil reservoir.

Finding the Oil

- In a much more sophisticated extension of the principle of echo sounders, sound waves are bounced off undersea sedimentary layers and recorded on thousands of underwater microphones (hydrophones) to find oil.

- The results are processed by computers to generate very detailed images of the geologic conditions of the area. Reservoirs of oil and gas are found in this way.

- The development of offshore oil has brought the societal need for all of this energy into conflict with environmental and aesthetic concerns.

Oil Spills

- In April of 2010, Deepwater Horizon, a state-of-the-art floating drilling platform was drilling a new well in 1500 meters (5000 feet) of water depth about 50 miles off the Louisiana coast.

- The rig had an uncontrolled release of natural gas from deep in the reservoir, which is called a **blowout**. Gas expands hundreds of times as pressure is released.

- A spark on the rig itself caused an explosion, and when firefighters were unable to put out the blaze, the rig sank and severed the pipe that connected it to the well on the sea floor 4000 feet below.

- The ensuing flow at the sea floor lasted 83 days before it was controlled, and a total of 5 million barrels of oil, plus large amounts of methane, were released.

- This spill is unique in the history of oil spills due the fact that the oil was injected not on the surface of the water but into deepwater—where some of the oil rose up to the surface and where a lot of it remained in deepwater.



© U.S. Coast Guard photo.

In April 2010, the Deepwater Horizon fire occurred in the Gulf of Mexico when the state-of-the-art, floating, dynamically positioned drilling platform was drilling a new well in 1500 meters of water depth.

- Although estimates from the 2010 spill vary, the U.S. government says that approximately 200 million gallons, or 5 million barrels, of oil was released. It is still the largest single-source oil spill to date.

- One of the problems of an oil spill is that the oil spreads along the surface of the water, which interferes with the exchange of gases through the water and fouls the skin or feathers of marine birds and wildlife.

- In addition, the oil that's floating on the surface of the water reaches the coastline and fouls it. In the Exxon Valdez oil spill in the Gulf of Alaska, the surface oil was by far the most ecologically devastating part of the spill.

- There are various methods that can be used to try to get rid of the oil in a spill, including **oil booms**, skimmers, dispersants, and time and weather.

Effects on Marine and Coastal Wildlife

- The Deepwater Horizon oil spill caused hypothermia in oil-coated birds, respiration problems for turtles and other marine mammals, and interference with reproduction in larval stages of many fish and shrimp.

- Harm to wildlife and ecosystems occurred, but the effects have proven to date to be less than many of the feared scenarios.

- Microbiology played an important role. Scientists detected tremendous blooms of hydrocarbon-eating bacteria that consumed both the oil and the methane gas.

- The long-term effect of oil—and dispersants—remains unclear, and there is some room for optimism. The lesson learned was that the offshore drilling industry must become better prepared for new environmental challenges with deepwater operations.

Other Offshore Resources

- In terms of offshore mineral resources, there are resources other than oil and natural gas that either are being exploited or could be exploited from the ocean: Sand and gravel can be dredged up from offshore regions to replenish beaches and to be used as fill material.

- Another mineral resource from the sea is the salt that's in the water. Most table salt is mined from geological deposits from sedimentary layers of rock, but a lot of salt is made by **salt evaporation** of saltwater in shallow evaporation ponds.

- If the salt is a resource, so is the water in the ocean. There are more than 15,000 **desalination** plants in operation because freshwater is a scarce resource in many arid regions of the world. The main methods of desalination are distillation and reverse osmosis.

Important Terms

blowout: The uncontrolled release of gas, oil, and/or water under pressure from a well.

caprock: Non-permeable marine rock that can trap in petroleum or natural gas that would otherwise buoyantly rise up through denser water and escape to the surface.

desalination: Process of removing salts from seawater by distillation or reverse osmotic pressure.

oil boom: A floating curtain of plastic placed into the water to contain spilled oil on the surface of the water.

reservoir rock: Porous marine rock or sediment layers that can hold large amounts of petroleum or natural gas.

salt evaporation: Production of sea salt for consumption by evaporation of seawater in open ponds.

Suggested Reading

Safina, *A Sea in Flames*.

Yergin, *The Prize*.

Questions to Consider

1. It has been said that petroleum (or natural gas) is just another form of solar energy. What is meant by that?

2. Obtain a map of offshore oil-producing regions around the world (readily available online). What do they seem to have in common, in terms of their locations in the ocean?

The Enduring Chemistry of Seawater

Lecture 12

The unique and surprising properties of H_2O, the water molecule, are responsible for the existence of a liquid ocean and a benign and relatively stable environment for life on Earth. Water is the only common substance that exists in gaseous, liquid, and solid form on the surface of Earth. The incredible heat-retaining capacity of liquid water has acted as a global thermostat throughout geologic time. Light penetrates only about 200 meters into the ocean—the photic zone—which controls the habitat.

Chemical Properties of Seawater

- The dissolved minerals (salts) in the ocean are in a remarkably stable state of chemical equilibrium, maintained by a balance among a variety of geological and biological processes—and chemical processes that keep the water the way it is.

- The water molecule is one of the most fundamental molecules that exists in nature and is composed of 2 hydrogen ions and 1 oxygen ion (H_2O). An ion is an atom of a particular element that has either gained or lost one or more electrons to give it a positive or negative charge.

- In the water molecule, 2 hydrogen atoms are sharing their electrons with an oxygen atom to form a molecule through **covalent bonding**, meaning the electron is shared between atoms. A covalent bond is a very strong bond.

- In this particular molecule, the 2 hydrogen atoms and 1 oxygen atom cause the molecule to be unbalanced, meaning that it is a polar molecule. It has a negatively and positively charged side to it.

- Because of this polar nature, the water molecules are held together by another kind of molecular bonding called **hydrogen bonds**. In liquid water, this hydrogen bonding gives water the special properties of being able to retain heat well and to resist evaporation.

- The atomic structure of the water molecule gives water the fundamental properties that make it liquid at the temperatures of the surface of Earth.

Ocean Water Chemistry

- Ocean water is water with a lot of chemicals dissolved in it. A solvent is the medium in which substances are dissolved. In the case of ocean water, the solvent is the water itself. The solute is that which is dissolved. In this case, the solute is the sodium ions.

- An ionically bonded substance, such as a salt crystal, is dissolved by the separation of the positively and negatively charged ions.

- A salt crystal is a bunch of chloride ions and sodium ions stuck together by hydrogen bonding. When put into the polar medium of water that has a charge imbalance, the chloride ions are pulled off and stick to the positively charged side of the water molecules, and the sodium ions stick to the negatively charged side of the water molecules.

- Water is an **aqueous solution**. Water is called the universal solvent and is very good at dissolving so many materials because it has a charge imbalance—a polar nature.

- Seawater is pure water with a small amount of dissolved salts and then many other different elements and compounds in small quantities. The term **salinity** refers to the total quantity of these dissolved inorganic solids, measured by weight.

- The ocean contains about 3.5% salts by weight: 1 kilogram of seawater has about 35 grams of these inorganic materials, which amounts to 5.5 trillion tons of salt dissolved in the entire ocean of the planet.

- The most abundant of the ions that are dissolved in ocean water are sodium and chloride, and fractions of a percent of the total amount include sulfates, magnesium, bicarbonate, calcium, and potassium. Some of these trace elements are important nutrients for life.

- There are many trace elements (measured in parts per million) that are important nutrients for life; some of the key ones are nitrogen, iron, and phosphorus, which are all important nutrients that are potential limiting factors for the growth of organisms.

- It is interesting that the ratio of major salts in seawater is constant all over the ocean—except, perhaps, in an estuary where freshwater is mixing directly with the ocean. This is known as the **principle of constant proportions** and as Forchheimer's principle.

- On the other hand, the salinity of the ocean—the total amount of those dissolved solids—varies over a relatively small range, between about 3.3% and 3.7%.

- Because of the convenience of the size of the numbers, oceanographers use per milliliter instead of percent to calculate salinity. Per milliliter is like percent, except instead of dividing by 100 to get the number, you divide by 1000.

Measuring Ocean Water Chemistry

- Oceanographers want to measure and take samples from the entire water column, which means that they need to take measurements at all depths and in many different locations.

- Salinity can be continuously profiled—instead of obtaining a single measurement using the weight of the water—by measuring the electrical conductivity of the water.

- Water is a conductor of electricity, but it is only a conductor to the extent that it has dissolved ions that can move around in the water. Absolutely pure freshwater is a poor conductor.

- The more dissolved compounds the water has and the more saline the water is, the more conductive it is; measuring the electrical conductivity of the water also measures the salinity.

- An electronic instrument can measure electrical conductivity of water, and it can profile the water with continuous measurements when it is lowered down through the water.

- Some chemical components can be measured directly, but for water chemistry, and perhaps even for microbiology, samples of the water must be obtained from different specified depths.

- In the early 20th century, Fridtjof Nansen, the early pioneering Norwegian oceanographer, invented something called a Nansen bottle, which was an open tube that was open on the bottom but closed on the top, trapping an air bubble. It was lowered down through the water, and it could be triggered with a pulley to flip over and take a sample of the water at a certain depth and bring it back up.

- An American oceanographer named Shale Niskin improved this by coming up with a system that instead has a tube that is open on both ends and is triggered to close both ends at specific depths to get a water sample. **Niskin bottles** are the method for water sampling that's used all over the world.

- The typical system that's used to do all kinds of water sampling and chemistry measurements is called a CTD/Niskin rosette, which is a series of Niskin bottles that are each individually triggered to capture a sample at different depths.

- A continuous profiler called a **CTD**—a conductivity, temperature, depth sensor package—records conductivity for salinity and then the temperature of the water through various depths all over the world's ocean.

- Anything that has dissolved materials in it can be measured on the pH scale, which is a measure of acidity versus alkalinity of a solution. The pH scale operates on a logarithmic scale.

- Each variation is a very large factor of variation in the pH scale from 0 to 14. Pure freshwater is in the center at 7; very alkaline, or basic, solutions are close to 14; and very acidic solutions are close to 0.

- Seawater has dissolved materials in it, so it's a bit alkaline—averaging about 8.1 to 8.2 on the pH scale. This balance is tremendously important for life in the ocean. The seawater alkalinity is maintained through the principle of constant proportions.

The Composition of Ocean Water

- Salts in the ocean are dissolved inorganic compounds, and they originate from the geological cycle. The erosion of rocks, the volcanic eruption of gases and solids, the hydrologic cycle, and various biological processes all combine to add salt to the ocean.

- Even though river water delivers dissolved material from the land to the ocean, there are some huge differences between the composition of river water and ocean water.

    - There's much more calcium in river water: About 12% of the dissolved solids in river water are calcium. The ocean contains only about 1% calcium.

    - Bicarbonate is almost half the composition of the solids in river water, but it's a tiny fraction of the solids in ocean water.

- There's a lot of silica in river water that comes from rocks, which are mostly silicates; silica is only present in trace amounts in ocean water.

- The ocean is loaded with chloride and sodium that are present in relatively small proportions in river water.

- River water and ocean water are not similar. The ocean's salinity is not simply a more concentrated product of the erosion and weathering of the landscape.

- The reason for these drastic differences is that the biology of what lives in the ocean actively alters the ocean chemistry. The missing silica and calcium that comes in from the river water is removed by organisms to make their skeletons and shells and is eventually sequestered into sediments after the organisms die.



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Shale Niskin created the Niskin bottle, which is lowered down into the water column and is triggered at specific depths to obtain a water sample.

- The other thing that's present in the water that's not present in the river water is the excess of various volatile components, which are mostly gases; they are called volatile components because they easily evaporate.

- The carbon dioxide, chlorine, sulfur, hydrogen, and nitrogen are all gases that come mainly from volcanic eruptions. In addition, water coming out of Earth's mantle through geological process carries with it a certain amount of these trace gases.

- The composition of ocean water is distinct from what's being put into it. Of all of these dissolved compounds, the proportions and amounts are nearly constant everywhere, so the ocean is in a steady state.

- However, it's not static; it's in a state of dynamic equilibrium. Ions are being removed from the ocean at the same rate they're being added, and all of this is balancing out in the seawater.

- In order for these materials to remain in constant proportions in the ocean, the ocean must have some sort of overturn or mixing time, which turns out to be about 1600 years for the entire ocean. In comparison to the residence time of most ions, this mixing time of the ocean suggests that it is well mixed.

- **Residence time** is the amount of a particular element in the ocean divided by the rate at which that element is added to or removed from the ocean. Residence time varies enormously for major seawater constituents. Chloride, for example, has a residence time of hundreds of thousands of years; sodium's is slightly less.

- The water in the ocean, interestingly, has a relatively short residence time at around 3500 years—even although there's a great deal of it. This is because water is part of the hydrological cycle, so it is continuously recycling through such processes as evaporation, condensation, and precipitation.

- Water circulates to great depth into the ocean floor, altering the properties of both the water and the rocks and sediments.

- Water and volatiles in sediments get recycled back into Earth's mantle at high temperatures, making melting possible.

Ocean Water and Plate Tectonics

- With volcanic input, sediment subduction, and sub-seafloor hydrology, ocean water and plate tectonics are intimately linked.

- Plate tectonics would have stopped long ago without a liquid ocean on Earth. Possibly, plate tectonics would not exist without life in the ocean because volatile compounds need to be subducted to replenish Earth's mantle.

- Biology, geology, and physical oceanography or chemical oceanography are all intimately linked in the ocean today.

Important Terms

aqueous solution: A mixture of compounds in water that are dissolved or separated into their charged ionic forms and are bonded to the water molecules through hydrogen bonds.

covalent bond: The strong bond formed when 2 or more atoms share common electrons; for example, the 2 hydrogen atoms and 1 oxygen atom of a water molecule.

CTD: An instrument lowered into the water to make continuous measurements of conductivity (for salinity), temperature, and depth.

hydrogen bond: The weak bond formed when polar ions or molecules are linked by attraction of their oppositely charged regions.

Niskin bottle: A device to take a water sample from a specified depth in the water column that has 2 open ends that can be triggered to close and seal in a water sample.

principle of constant proportions: The ratio of major salts in seawater is everywhere the same in the world's ocean—though concentration (salinity) may differ. Also known as Forchhammer's principle.

residence time: The amount of an element in the ocean divided by the rate at which it is added or removed; a measure of the average time the element stays in seawater.

salinity: The total amount of dissolved solids in water, expressed by weight per unit volume.

Suggested Reading

Open University, *Seawater*.

Sverdrup and Armbrust, *Introduction to the World's Oceans*, chap. 4.

Questions to Consider

1. What's the difference between the salinity and the proportion of salts in seawater?

2. Why hasn't the sea simply become progressively saltier over time?

How the Physics of Water Controls the Ocean

Lecture 13

The dissolved minerals (salts) in the ocean are in a remarkably stable chemical equilibrium due to vigorous global mixing, which is governed by density differences due to temperature and salinity. The chemistry of the ocean is the same all over the world, but the concentration, or salinity, varies. Salinity and temperature determine differences in density that govern the stratification of shallow and deep water in the ocean. Biological processes regulate ocean chemistry; thus, life on Earth controls its own environment.

The Properties of Water

- The unique and surprising properties of the water molecule H_2O are responsible for the very existence of a liquid ocean and a stable environment for life on Earth.
    - Water is the only substance that exists in solid (ice), liquid (water), and gaseous (water vapor) states at Earth's surface conditions.
    - The heat capacity for water is very high, so the global ocean regulates Earth's surface temperature.
    - Remarkably, solid ice is less dense than liquid water.
    - Light can only penetrate a limited distance through water.
- Heat is the total amount of energy stored in a substance as the random vibration of a quantity of atoms and molecules.

- Temperature is a measure of this stored energy through an object's response to input or removal of heat.

- **Heat capacity** is a measure of the heat required to raise the temperature of 1 gram of a substance by 1°C. Heat capacity is measured in calories; pure water has a heat capacity of 1 calorie.

- Water has a tremendously high heat capacity, meaning that it can absorb or release a lot of heat while not changing much in temperature.

Forms of Heat

- There are 2 different forms of heat: sensible heat and latent heat. **Sensible heat** is the heat absorbed or released during a change in temperature. It's the amount of heat that you can sense (with a thermometer).

- **Latent heat** is the heat that must be absorbed or released to change the state of some material from liquid to solid or from liquid to vapor. For example, freezing or evaporating water requires the input of a lot of latent heat, but the water doesn't necessarily change in temperature.

- The sensible heat for changing the temperature of water is 1 calorie per degree per gram of water. As heat energy is added to water in a pot, it starts raising the temperature of the water—1 calorie of energy input per gram results in 1 degree of temperature rise—until it reaches the boiling point, which is 100°C.

- At the boiling point, the water starts to boil and turns from liquid into water vapor. You can't make the water any hotter than that, but you're still adding lots of energy, feeding that energy into the latent heat of evaporation of the water. It takes 540 calories per gram in order to convert the water into water vapor.

- Similarly, if you took this same pot of water and put it in the freezer, you could lower its temperature quickly down to the freezing point, but then it would take what's called the latent heat of fusion—80 calories per gram—in order to turn it into ice.

- Both the high heat capacity of liquid water and the large latent heats of fusion and evaporation mean that the ocean is a phenomenal global thermostat that regulates the temperature of the surface of the planet.

- The high heat capacity of liquid water means that the water holds a lot of heat in without changing the temperature very much—a property called thermal inertia.

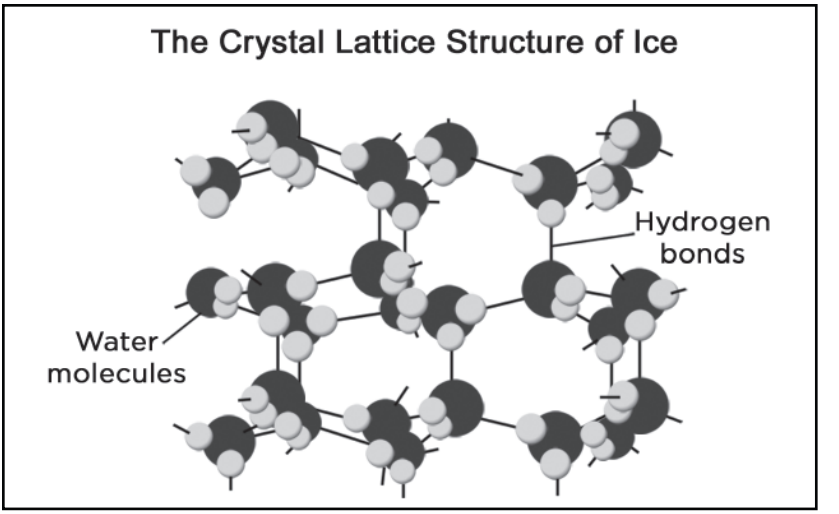
- The latent heats of fusion and evaporation mean that the heat content of the ocean can change pretty drastically without going outside the temperature range between 0°C, or 32°F, and 100°C, or 212°F.

- These properties result in the ocean being a thermal mass for the planet that prevents very large swings in temperature between times of the day and between seasons, which is true for the entire planet.

- In comparison, Mars has night-to-day changes in temperature that can range up to as much as 150°F, which is what it would be like on a planet like Earth that did not have a liquid ocean on the surface to modulate temperature swings.

- This global ocean thermostat has persisted throughout geological time for as long as the ocean has been around because it's a basic property of the physics of water.

- The high heat capacity and latent heats of water have kept the global ocean from either freezing solid or boiling away for several billion years. These properties have an enormous stabilizing influence on Earth's habitability, and they keep Earth's surface in the comfort zone in which liquid water exists.



The Properties of Ice

- Frozen water—ice—is a very unusual substance. It is a mineral that has a crystalline structure. When the polar molecule H_2O bonds together to form the crystal lattice structure of ice, there are a few effects.
    - The hydrogen bonds go from the interionic angle of 105° out to 109° so that they can interlock with each other and bond to the oxygen atoms of the molecule next to them.
    - Water expands about 9% as it freezes.
    - Ice is less dense than water, causing ice to float on water.
- Ice floats on water and creates a kind of thermal blanket on top of water; therefore, any ice that forms in the ocean is going to form on the surface, keeping the liquid water below, because of the density difference.

- If ice were denser than water, the ice crystals would sink to the bottom, accumulating in the ocean. Then, more would form at the top, and pretty quickly most of the ocean would be frozen solid—causing Earth to be uninhabitable.



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Solid ice is quite unusual. It's less dense than liquid water, and it's actually a mineral with a crystalline structure.

- Water density and temperature are even stranger than ice density and temperature in some ways. Like most substances, when you warm water up, it expands a little bit and becomes less dense. So, the density of water decreases with higher temperature.

- As you near the freezing point of water, however, it reaches a maximum density at about 4°C. Water that's warmer is less dense, but interestingly, water between 4°C and 0°C is also less dense. Then, when it actually freezes, it jumps to a significantly lower density.

Seawater and Heat

- The dissolved salt in seawater has several important effects on its properties. The fact that there are a bunch of dissolved solids (salinity) raises the density: Pure water has a density of 1 gram per cubic centimeter, but seawater has a density of about 1.03 grams per cubic centimeter.

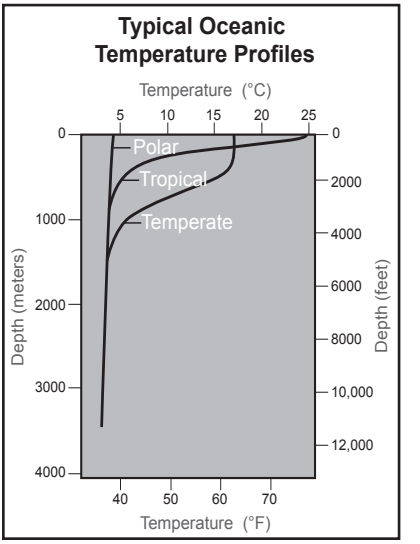
- A second property is that the saltiness of the water acts as a kind of antifreeze. Seawater with its salinity freezes at a temperature of −1.91°C, so it delays the freezing a little and inhibits the formation of ice.

- Finally, when seawater actually does start to freeze, the freezing of seawater makes freshwater crystals, excluding all of those dissolved solutes—almost like a distillation process. The water that is left behind has a higher salinity and, therefore, a higher density than the water in the ocean around it.

The Density of Seawater

- Like most substances, seawater expands and becomes less dense as it warms. The density of seawater controls the layered structure of the deep ocean. Solids are usually denser than liquids of the same substance—but water, again, is unusual.

- Basically, ocean water forms stable layers by density; it is stratified by density. There's a surface zone, a deep zone, and a zone in between.



- The surface zone is a region where waves and currents keep the water continuously stirred and well mixed. It has a pretty uniform density, but the surface of the water tends to be low density mainly because lower-density water rises and higher-density water sinks.

- The deep zone comprises about 80% of the volume of the ocean and is below a depth of about 1000 meters. The deep zone is a mass of relatively dense, cold water—that is not mixed up by waves and currents found at the surface—with standard seawater salinity.

- In between the surface zone and the deep zone is a region called the **pycnocline**, the zone in which density increases strongly with depth—starting below a few hundred meters to about 1000 meters.

- The density of seawater is a function of both salinity and temperature. Therefore, the pycnocline is reflected as a gradient for these other properties as well.

- The **thermocline** is the depth zone of a strong temperature gradient. The pycnocline is also very typically a thermocline: Water near the surface of the ocean is warmer and relatively well mixed. As depth increases, water goes through a large gradient, and then the deep ocean is not quite uniform in temperature but pretty close.

- The water column also has a salinity gradient called the **halocline**. All of these gradients are a reflection of the same property of water: density.

Water Pressure

- Pressure increases with depth in the ocean. Pressure is a function of the weight of the medium—the fluid medium—that surrounds you.

- On the surface of Earth, we're under a pressure of 15 pounds per square inch, which comes from the weight of the atmosphere—the physical weight of the gas, the air, above our heads. The atmosphere is not very heavy; it doesn't have much density.

- The ocean, on the other hand, has a lot of density: 1 gram per cubic centimeter. Water is incredibly heavy, and the pressure increases as the depth of the water increases by about 1 atmosphere—1 equivalent of atmospheric pressure—for every 10 meters down in the ocean.

- A scuba-diving human being can stand a pressure of maybe 3 to 4 atmospheres. The pressure chamber of a submersible allows humans to reach higher pressures because the submarine itself is under that pressure, and the pressure chamber keeps the pressure off of the person.

Light Penetration in Ocean Water

- Light penetrates the ocean water to a certain degree, and a zone of the ocean is lit up—the photic zone, which typically reaches about 100 to about 250 meters of depth in the ocean. The majority of the ocean, then, is in the aphotic zone.

- Within the photic zone, light is absorbed by the polar properties of water molecules, and the energy—the wavelength of the light—comes in and vibrates those molecules.

- The water molecules then absorb and scatter the energy of the sunlight differentially by color, and because each color of light in the spectrum has a slightly different wavelength, different wavelengths affect the water molecules differently.

- Blue light has the ability to penetrate the farthest into the ocean, so it's scattered back from the water, making the water look blue. All the other light has already been absorbed and doesn't penetrate as far, so we don't see as much of it when we look down into the water.

- The light penetration into the ocean exponentially declines with depth. Much of the life in the ocean depends on sunlight and photosynthesis, so it is confined to the upper reaches of the photic zone.

Important Terms

halocline: A strong gradient in salinity with depth; largely coincides with the pycnocline and thermocline.

heat capacity: The amount of heat energy absorbed by a substance to raise its temperature a specified amount, also known as thermal capacity.

latent heat: The heat energy that must be absorbed or released to change the state of a material by evaporation or freezing, producing no temperature change.

pycnocline: A strong gradient in density of seawater versus depth.

sensible heat: Heat energy that results in a change in temperature.

thermocline: A strong gradient in water temperature versus depth that separates warm surface waters from the vast volume of cold, deep water.

Suggested Reading

Medwin, *Sounds in the Sea*.

Sverdrup and Armbrust, *Introduction to the World's Oceans*, chap. 5.

Questions to Consider

1. Latent heat as a concept is not very intuitive. Can you think of any examples of latent heat changes in everyday life? (Hint: Why do we perspire in hot weather?)

2. Do you think the depth of the photic zone varies around the world's ocean? What factors might govern variations?

Waves—Motion in the Ocean

Lecture 14

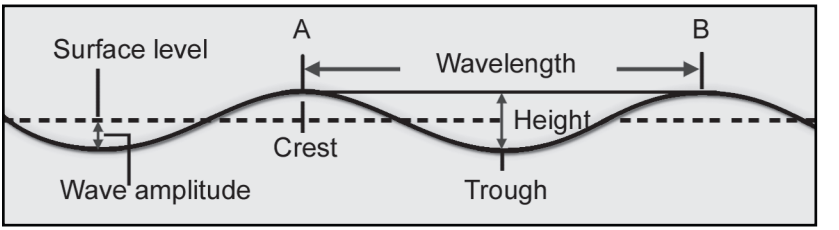
Ocean waves are generated by the drag of wind blowing over water and can travel as swells thousands of miles from where they are generated; their size and speed are governed by whether they travel through deep or shallow water. Wave size and type is governed by wind speed, duration, and fetch. Normal waves affect only the uppermost levels of the ocean. Waves refract around shallow and deep portions of the near-shore ocean floor, changing direction and size.

Water in Motion

- Waves are disturbances, and ocean waves—just like waves of any type—are simply disturbances of a medium that transmit energy while not actually transferring mass, at least not transferring it very far.

- A stone dropped into a pond creates a ripple, a disturbance of the surface of the water. Waves move energy across the sea surface.

- The water doesn't travel with the waves across the ocean; instead, the wave is a propagation of energy. For example, if something is floating on the water and a wave goes by, it ends up more or less in the same place it started out. This is described as the **orbital motion** of waves.



Anatomy of a Wave

- Ocean waves, as well as other types of waves, have crests and troughs, or highs and lows. The difference between the high and the low is defined as the wave height. Wave amplitude is half of the wave height because amplitude is defined from the zero line to either the crest or the trough.

- Wavelength is the horizontal distance between a point on one wave and the comparable reference point on the next wave. From one crest to the next crest is a certain distance, for example.

- A **wave period** is defined as the time it takes 2 successive crests to pass a stationary point. The wave speed is the velocity that the wave is moving laterally, which equals the wave length divided by the wave period. In oceanography, wave speed is often referred to with the term **celerity**.

- A wave in the open ocean that does not interact with the bottom is called a **deepwater wave**, which is defined as any wave where the water depth is greater than half the wavelength. The orbital motion of a wave—the bobbing up and down that occurs at the surface—impacts the water to a certain depth, but it's not an infinite depth.

Types of Deepwater Waves

- There are 2 main types of deepwater waves: capillary waves and wind waves. **Capillary waves** are the small ripples that travel across the surface of the water that are created by some disturbing force to the surface—usually the wind.

- **Wind waves**, by contrast, are the larger-scale waves that are typically thought of as ocean waves. They evolve from the capillary waves with more time and continued wind action blowing across the water. They are a coalescence of individual capillary waves building up to a larger size.

- Waves are classified not just by what creates them—called a disturbing force—but also by what makes them propagate and travel through the water, which is called a restoring force.

- The resorting force smoothes waves back out after a disturbing force, such as the drag of the wind, pulls the water up.

- Still water is flat because the surface of water has a certain amount of surface tension based on the molecular bonds of polar water. When waves are small enough to be capillary waves, what flattens them back out is surface tension that wants to snap everything back into a level state.

- The restoring force for capillary waves is surface tension, but the restoring force for wind waves is gravity because water wants to find its own level—not build a little hill.

- The typical wavelength for capillary waves is very small: The maximum wavelength is less than an inch, based on how strong the force of surface tension can be. Wind waves, on the other hand, can have a wavelength that is anywhere from less than a meter up to more than 150 meters.

Capillary Wave Formation

- Capillary waves form by the wind blowing over the water and pulling on the water surface by the molecular adhesion of the gas to the water, which builds up a small hill.

- On the upside of that hill, the wind separates from the water; on the backside, there's a low pressure zone in which the wind pressure dies down, causing the wind to separate from the water. Together, these processes create a small hill.

- Pressure is higher on the upwind side than it is on the downwind side, setting that small hill in motion, which is the capillary wave moving across the water.

- Capillary waves build up where the wind is forcing them and dance across the surface of calm water, developing ripples. If the wind continues to blow, the ripples will coalesce into wind waves, building up longer wavelengths and traveling farther as their wave height grows.

- Choppy seas reach a specific ratio of wavelength to wave height that is based on the cohesion of water and gravity. The ratio of the wavelength to the height can be a maximum of 7 wavelengths to 1 height; if it exceeds that steepness, it generates turbulence in the form of white caps and foam.

- The height of these irregular, choppy waves in the area of wind-wave formation is called the sea or sea state, which is confusing, but it is just an area of the ocean over which the wind blows for an uninterrupted distance over a relatively uninterrupted period of time.

Properties of Waves

- The factors that control the variety and size of waves are the speed of the wind, the duration that the wind blows in a relatively constant manner, the wind **fetch**—which is the distance over which the wave-generating force occurs—and the original state of the sea.

- A fully developed sea is one that has reached the maximum possible wave height for the wind speed, duration, and fetch. The Beaufort scale, which is used by mariners to describe the sea state, depends on the wind force.

- The waves don't stop when the wind stops blowing. In fact, the waves become more regular and well developed; these mature waves that have spread away from the windy area are called sea **swells**.

- Swells can propagate tens of thousands of kilometers away from where a wave is formed because they move fairly efficiently through the water in terms of transferring energy across the ocean's surface.

- Swells have a particular speed with which they travel over the ocean that is a function of the wavelength and the period of the wave. The speed, or celerity, of a deepwater wave is the wavelength divided by the period.

- The wavelength and the period are also related by a 1:7 ratio, so—through mathematical substitution—the speed of the wave is 1.56 times the period of the wave, and the speed squared is 1.56 times the wavelength of the wave.

- Therefore, a deepwater wave travels at a velocity that is dependent on its wavelength. A wave with a longer wavelength travels faster, farther, and is higher than a wave with a shorter wavelength.

- Waves come from the stormiest parts of the ocean. For the most part, large ocean swells start out in either the high northern latitudes or the high southern latitudesn—in the North Pacific and Southern oceans.

Breaking Waves

- As a wave approaches shallow water, the orbital motion of the deepwater wave starts to impinge on the bottom, moving sediments back and forth or dragging on the rocks and the reef. This motion imparts a viscous drag—because of the viscosity of water on the wave itself—that tends to make the wave slow down.

- Deepwater waves become intermediate-water waves and shallow-water waves. **Shallow-water waves** occur in a region where, by definition, the water depth is only 1/20 or less of the wavelength, which means the wave motion moves across the bottom very strongly.

- The speed of a shallow-water wave is purely a function of water depth; the wavelength doesn't matter once it's met the definition of being a shallow-water wave.

- Everything in between 1/20 of the wavelength and 1/2 of the wavelength is the intermediate region because it's a transition zone where the friction and properties of the water are changing from deep water to shallow water.

- For the intermediate water waves, the speed is complicated, but the waves are certainly slowing down as a shifting function of both water depth and wave properties in that zone.

- What happens as the wave train approaches the shoreline and starts to break? As the wave drags at the bottom, it slows and becomes more peaked. Waves break where the ratio of wave height to water depth is about 3:4. Due to circular orbits, the top of the wave is moving faster than the bottom as water shallows, so it spills over.



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The huge ocean swells that surfers covet start out in either the high northern or the high southern latitudes.

Types of Breaking Waves

- There are 3 types of breaking waves, and they depend specifically on the characteristics of the slope and shape of the ocean bottom where the wave is coming into shallow water.

- Spilling breakers form on a relatively flat ocean bottom with a long distance of energy dissipation as the crest spills over the front of the wave.

- Plunging breakers form on moderately steep ocean bottoms with a rapid curl and plunge of the wave front with rapid energy dissipation.

- Surging breakers form on very steep—greater than 15°—slopes. These do not actually break but surge forward, maintaining energy and often reflecting off seawalls and breakwaters, for example.

Wave Refraction

- Ocean waves, like all waves, undergo **wave refraction**—meaning they change the direction that they're propagating as they come into the coastline.

- If a wave is coming straight toward the shore with the wave crest perfectly parallel to the shoreline and if the ocean bottom is perfectly flat, then the wave might all break at once. What more typically happens is the wave comes in at a bit of an angle, making an oblique angle to the shoreline.

- Then, the side of the wave that's closer to the shore on the same crest will be in shallower water than the same crest farther out offshore, and the part that's in shallow water slows down.

- At this point, the wave front doesn't break; as a wave it breaks, but the wave front is continuous. Instead, the wave front starts to bend around to become more parallel to the shoreline.

- When there are headlands of rock and bays or beaches behind them, the open-water wave comes in, but the rocky point of land usually has shallower water offshore, so the waves converge on that headland and focus their crashing energy on the headland and tend to erode it away more.

- On the other hand, the waves focus their energy away from the nearby bays, which have calmer water as a result. The waves are bent into the same shape as the bay itself; the center of the bay usually has the deepest water, and the points over to either side have shallower water, so the wave reflects that.

Important Terms

capillary waves: Ripples in water defined by the dominance of surface tension as the restoring force.

celerity: The speed at which a water wave moves; equal to wavelength divided by wave period.

deepwater wave: A wave in water deeper than 1/2 the wavelength.

fetch: Linear distance over which relatively constant wind blows, forming wind waves.

orbital motion: The circular path taken by a water particle as a wave passes by, moving it first back and upward then forward and down to return to its starting point.

shallow-water waves: Formally, all waves in water shallower than $1/20^{th}$ of the wavelength.

swell: Waves that have left the area of development and are propagating across the sea surface.

wave period: The time elapsed from the passage of one wave crest to the next (or any equivalent points on a cyclical wave).

wave refraction: Bending of the orientation of wave crests by differential wave speed caused by local differences in water depth.

wind waves: Waves caused by wind drag on the water surface and defined by the dominance of gravity as the restoring force.

Suggested Reading

Butt, Russell, and Grigg, *Surf Science*.

Holthuijsen, *Waves in Oceanic and Coastal Waters*.

Questions to Consider

1. Could a ship's wake start a train of swells moving thousands of miles across the ocean? Why or why not?

2. Next time you're at the beach or coast, observe the waves. Can you see evidence for wave refraction?

Rogue Waves and Tsunami

Lecture 15

Tsunami and rogue waves are special classes of destructive waves capable of traveling long distances across the ocean to strike with little warning. Tsunami result from the sudden displacement of the ocean floor and overlying water due to an earthquake or landslide. Tsunami have wavelengths of hundreds of kilometers and therefore travel according to the rules of shallow-water waves—even across the deep ocean at ultrahigh speeds. Rogue waves are single waves that form by constructive interference of 2 or more swells; they can reach heights of 100 feet or more, creating a hazard for ships at sea.

Pathological Waves

- Waves can be a tremendously destructive force. For example, very large swells and rough seas exist in gales.

- Tsunami and rogue waves are special classes of destructive waves that form by different processes; they are not simply wind waves that have become out of control.

- The research vessel *James C. Ross* sailed in the roaring forties, which is an area that is near Antarctica in the Southern Ocean. This area has ferocious weather that causes the heaviest seas on Earth.

- Very large waves form where fetch is great; in the Southern Ocean, for example, the westerly winds circle Antarctica continuously, creating large **building seas**. The height of these large waves can reach 15 meters (50 feet), and their wavelength is so great that they present a hazard—even to large ships that have been built to withstand such seas.

- The RRS *Discovery* is a British research vessel that sailed off the coast of Scotland in a region of the North Sea notorious for very large, wind-generated, storm-generated waves. In 2000, the crew recorded, for the first time, waves with a significant wave height, which requires that 33% of all the waves are at a height of 61 feet or more with spikes much higher.

- Computer models by physical oceanographers suggested that wind-generated waves could never reach that height, but the crew brought back the data that proved they could.

- In 1933, the USS *Ramapo*, a naval tanker vessel, was out in a huge storm in the Pacific Ocean that lasted for days. Lieutenant Frederick Marggraff sighted a wave from the bridge deck to the crest of the wave behind it and calculated its height to be about 34 meters, or 112 feet—by far the highest documented wave at that time.

Types of Wave Interference

- Wind-generated waves can become even larger when different trains, or different sets of wind waves, interact with each other in ways that include constructive and destructive interference.

- A wave is cyclical; it has peaks and valleys. If there are 2 sets of waves coming from different directions and the second wave train is superimposed over the first, they will interfere with each other.

- If the 2 sets of waves are moving in the same direction but with slightly different wavelengths, then in some places the peaks of both waves will superimpose on each other—called constructive interference; in other places, the peak will superimpose on the trough, or vice versa—called destructive interference.

- With constructive interference, whether the waves are superimposed peak to peak or trough to trough, the result is a wave with an especially large amplitude. With destructive interference, the wave is damped out with a smaller amplitude.

Rogue Waves

- A **rogue wave** is a freak wave—or a short series of freak waves—that is much larger than any wave before or after it. A rogue wave is also larger than the theoretical maximum for a fully developed sea.

- Rogue waves, also referred to as episodic waves, are poorly known and understood. Waves that reached heights of 100 feet or more seemed to defy known physics, and stories of them were long discounted by physical oceanographers.

- In 1916, Ernest Shackleton described a 100-foot lone wave in crossing from Antarctica to the South Georgia island. In 1978, an 850-foot cargo ship MS *München* was out in the middle of the ocean, sent out a distress call that indicated they experienced a sudden onset of enormous waves, but was never seen again.

- According to Susan Casey's gripping book *The Wave*, every year, on average, more than 2 dozen large ships sink or go missing—along with their crews. Most are cargo and tanker vessels, and most must be victim of enormous swells and rogue waves formed through constructive interference.

Tsunami Waves

- **Tsunami** waves are generated by some completely different processes that have to do with underwater earthquakes or landslides. Another term for tsunami waves is seismic sea waves because they are generated by earthquakes.

- Throughout all of history, plate tectonics have caused great earthquakes on the coastlines, or offshore, that have generated large tsunami. It seems that more tsunami have been reported in the news recently, and in fact, there have been more than there had been for 40 years.

- After a 40-year period of few tsunami of great significance around the world, tsunami disasters roared into the news in 2004 and 2011 with the Indian Ocean and Japan events—as well as the 2010 tsunami in Chile.

- From 1944 through 1964, before that 40-year hiatus, a number of major tsunami occurred that were caused by large earthquakes in the ocean. That hiatus had been a pause—probably a statistical gap for an infrequent event.

- Tsunami is a combination of 2 Japanese words: *tsu*, which means harbor, and *nami*, which means wave. A tsunami is a harbor wave, and it was given that name at least 1000 years ago in Japan because these were the waves that overwhelm even the protected harbors, the regions where water doesn't normally come in.

- They're not tidal waves; they have nothing to do with the tides. They are mainly generated by a specific type of event—an undersea subduction-zone earthquake.

- Both Indonesia and Japan are subduction zones, places where the ocean-floor plate is being carried beneath the rocks of the continent, or the Indonesian and Japanese islands in these 2 cases. At these types of locations, the plates are converging on one another.

- Convergent zones are the sources of virtually all the large tsunami that have occurred in recorded history. One plate goes down while the other plate rides over it, but at the boundary between them—especially in the uppermost part of Earth's crust—the 2 plates stick together.

- As they stick, the plate going down buckles the other plate up, storing elastic strain. Finally, after hundreds of years of accumulated plate-tectonic motion, the buckled plate exceeds the strength of the rock above it and pops forward, pushing the land out underneath the water, which flings the water up into a tsunami.

- Tsunami result from the sudden displacement of the sea floor and overlying water due to an earthquake—or landslide. Tsunami begin with a very long wavelength of about 100 to 200 kilometers, so they are shallow-water waves—even in the deep sea.

- Tsunami height grows in shallow water, inundates the coastline as a surge that takes many minutes to reach peak height, and then multiple arrivals of peaks and troughs occur.

Tsunami in the Pacific

- In 2011, because there was an earthquake that took place in Japan before the arrival of the tsunami, people on the coastline had some warning that a tsunami was likely. As a result, people started videotaping the wave at its inception, which is why we have the best record of a tsunami from this event.

- The tsunami slowed down to only as much as about 30 miles an hour in shallow water, but the height grew many times its initial height. It washed across the landscape, arriving not so much as an enormous breaking wave at first but more like a tidal bore.

- The open-ocean height of the tsunami was just a few meters, but because of the shortening and growing and also because of the funneling effect of some harbors where there was deep water in a canyon off shore, the tsunami height was very large, which is why so many people lost their lives.



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Coastal towns in Oregon or Washington that are located at sea level have signs that warn of tsunami hazard zones.

- The maximum height that the tsunami reached on land has been documented at around 38 meters in some of the villages along the north coast of the island of Honshu in Japan.

- When an earthquake happens and the land suddenly releases all that stored energy that comes from plate tectonics, it not only launches the tsunami, but it can also have an effect on the level of the land. The offshore region pops up, but that means that the onshore region drops down.

- Tsunami in the Pacific Ocean have occurred many times in the 20th and 21st centuries, and they don't just do damage locally. They also can do damage because tsunami are such a long wavelength away; they travel across great expanses of the open ocean without dissipating in energy much at all, so they can arrive on the far side of the Pacific with a fairly large magnitude.

- In the 1940s and 1960s, several very large earthquakes—such as the magnitude-9 Chilean earthquake of 1960—launched tsunami that traveled across the Pacific Ocean and did damage in Hawaii and in some of the same regions of Japan that were damaged in 2011.

- In 1946, an earthquake in the Aleutian Islands caused a lot of damage in Hawaii and also inundated and flooded coastal regions in California.

Tsunami and Technology

- Long-distance tsunami are a hazard, but we have an effective long-distance tsunami warning system on the planet today.

- There are a number of buoys that have been placed in the ocean called **DART stations**, which have a seafloor pressure sensor that measures the height of the tide and sends data to satellites and then to tsunami warning centers.

- If you look at a map based on computer simulation of where wave heights are predicted to be, there are certain regions that get more tsunami than others—even at the same distance away from the original earthquake's source.

Tsunami in North America

- On January 26, 1700, at about 9:30 at night, there was a magnitude 9.0 earthquake that reached from Vancouver to northern California. We know this occurred because of historical records of a puzzling tsunami that struck Japan the next day.

- We know that tsunami have occurred in the Pacific Northwest in the United States. In fact, there have been several of these earthquakes in the geological record that suggest that, on an average reoccurrence time of 300 to 500 years, tsunami can occur again in this region.

Important Terms

building sea: Area of surface water where wind action is actively creating and growing new waves.

DART station: Stands for Deep-ocean Assessment and Reporting of Tsunamis. A buoyed transmitter with a seafloor pressure sensor that can detect tsunami waves as they travel across the open ocean, providing early warning information.

rogue wave: Any wave or short series of waves at least 2 times larger than prevailing waves in the area and time—and larger than the theoretical maximum for a fully developed sea.

tsunami: A wave train produced by displacement of water due to sudden mass movement of the sea floor caused by an earthquake or undersea landslide.

Suggested Reading

Atwater, Musumi-Rokkaku, Satake, Tsuji, Ueda, and Yamaguchi, *The Orphan Tsunami of 1700*.

Casey, *The Wave*.

Parker, *The Power of the Sea*.

Questions to Consider

1. How is it that a tsunami in the open ocean is classified as a shallow-water wave? What implications does this have for how it moves as it spreads across an entire ocean basin?

2. Based on what you know from this lecture, would a surfer be likely to be able to take advantage of a rogue wave?

Tides in Theory and Practice

Lecture 16

Tides are the result of the gravitational attraction of the Sun and the Moon on the ocean's water, modified by the irregular shapes of the sea floor and coastlines. Newton's equilibrium theory of tides explains them based on the simple interactions of the ocean, Earth, the Moon, and the Sun; Laplace's dynamic theory of tides adds the effects of streaming water in motion. Tides are affected by amphidromic circulation, and depending on location, tides can be diurnal, semidiurnal, or mixed. In special cases such as confined bays and river mouths, special tides form as macrotidal ranges and tidal bores.

Ocean Tides

- The waves with the longest wavelengths on the planet are the ocean tides. Tides are, in fact, waves, and their wavelength is equal to 1/2 the circumference of Earth: 20,000 kilometers. The tides, like the tsunami, are counterintuitively a shallow-water wave even in the open ocean.

- Ocean tides can be defined as periodic and short-term changes in the height of the ocean surface caused by gravitational attraction of the Moon and of the Sun when combined with the rotation of Earth.

- Simple causes—the effect of the Moon and the Sun and the spin of Earth—produce pretty complex effects due to the fact that Earth has an irregularly shaped sea floor. It has coastlines and continents that interfere with the motion of the tides around the planet.

- Tides have long been a part of human history. Much of our interaction with the ocean is at the coastline, so the tides play an enormous role in various kinds of human activity.

Equilibrium Theory of Tides

- The equilibrium theory of tides says that the tides are caused by gravity and inertia on the planet. In addition, the tides are associated with the Moon and the Sun.

- Isaac Newton's law of universal gravitation states that any 2 objects that have mass have an attraction to each other based on the force of gravity. In fact, that is what generates the force of gravity.

- The force of gravity is the mass of one object times the mass of the other object—Earth and the Moon, for example—times some constant number G, which is called the universal gravitational constant: $F = G(m_{\text{Earth}} \times m_{\text{Moon}})/r^2$, in which r is the distance between their centers.

- The distance between the center of mass of the 2 objects defines the gravitational attraction between them. Earth and the Moon attract each other by a certain amount of gravity, and Earth is much bigger than the Moon, so that's why the Moon is in orbit around Earth.

- The tides are caused by the pull of the Moon because it pulls on the water of the ocean in addition to the planet itself. The ocean has mass and, therefore, gravity; the ocean is part of a gravitational system.

- The forces on the ocean, just like the forces on Earth, can be calculated based on the distance to the Moon and the mass of the Moon. The Sun is far more massive, but it is much farther away than the Moon.

- The tides are the resolved force of gravity on the ocean at the surface of Earth and are about 2/3 due to the Moon and about 1/3 due to the Sun.

- A key additional factor is the rotation of the Earth-Moon system and the centrifugal forces on the ocean. It's not exactly correct to say that the Moon simply revolves around Earth; instead, the 2 of them revolve around their common center of mass.

- The ocean itself is being pulled toward the Moon, and the water of the ocean rushes toward the Moon because of the gravitational attraction of the Moon.

- There's a bulge in the ocean several meters high on the side of Earth that faces the Moon. Because the 2 are rotating around each other, there's also an equal and opposite bulge pointing away from the Moon in the exact opposite direction of Earth based on centrifugal forces.

- The tide rises and falls twice per day in most areas because they're first going through the bulge that's toward the Moon and then going through the bulge that's away from the Moon as Earth spins around on its daily 24-hour axis.

- What is actually happening is that the tide is pointing toward the Moon and away from the Moon all the time, and Earth is spinning around underneath the tides. The ocean is pointing toward the celestial objects, and the land is spinning around.

- Because a day is 24 hours long, the tide comes a little later each day. Over the course of that 24 hours, the Moon has moved 1/28 of its monthly cycle around Earth. Therefore, the tide comes in 50 minutes later, on average, each day of the month.

- The tidal bulges follow the lunar position, but the Moon doesn't stay over the equator of Earth: It has a tilt up to 28.5° either north or south of the plane of the equator.

- As the tide rolls around Earth, the lunar position complicates the tides such that if you're at a particular latitude in the Northern Hemisphere, you see a higher tide for the first tide of the day and then a lower high tide for the second tide of the day—a cycle that isn't completely symmetrical as the day goes by.

The Sun and the Tidal Cycle

- The Earth-Moon system is traveling around the Sun all year long. Sometimes the Moon is lined up with the same line, or plane, between Earth and the Sun, and sometimes it's at a right angle to it.

- When the Moon is lined up with (in between) Earth and the Sun, that phase is called the new Moon because we don't see the reflective light of the Sun coming from the surface of the Moon at all. The lunar-tidal effect and the solar-tidal effect are lined up with each other, and the tide is especially large—called a **spring tide** because the tide springs up onto the beach.

- Halfway through the lunar month, the Moon is on the opposite side of Earth from the Sun and is in the full Moon phase, but the gravitational forces are still lined up with each other, causing another especially large tidal period.

- In contrast, in the quarter Moon phase, the Moon's gravitational attraction is at right angles to the Sun's gravitational attraction. The high tide still essentially follows the lunar position, but the Sun and the Moon partially cancel each other out, so the tidal range is subdued—called **neap tides**, which are the tides that have the smallest range over the course of a month.

Tidal Record

- The tidal record for a typical month is that there is constructive interference of the solar and lunar wave, or gravitational tide, during the spring tide. There is destructive interference during the neap-tide period.

- The Earth-Moon system doesn't go around the Sun in a circular orbit. It goes around the Sun in an elliptical orbit, so there's a seasonal, cyclical variation in the height of the spring tides or of the neap tides.

- Again, Newton's law of universal gravitation states that the force of gravitational attraction depends on the distance. Therefore, when Earth is closest to the Sun, then the tidal range is highest and strong. When Earth is farther away from the Sun, the tidal range is lower because the Sun's gravitational attraction is smaller.

- In the Northern Hemisphere, Earth is closest to the Sun in wintertime, and the tidal range is highest. The largest tides that flood the coasts and cause the biggest tidal range tend to come in winter in North America.

Dynamic Theory of Tides

- The equilibrium theory of tides says that the water has to follow the Moon over the course of a daily cycle. It turns out that the speed, the celerity of the tidal wave, should be 1600 kilometers an hour in order to keep up with going all the way around Earth—which is not achieved.

- Instead, the tides are a wave with a wavelength of 20,000 kilometers, so they have to be shallow-water waves even in the deep ocean. Shallow-water waves have a velocity that's determined by their water depth—not by their wavelength.

- Because of the wavelength of tides and because the continents get in the way, complex water motions are produced, which are accounted for in the dynamic theory of tides.

- Dynamic theory is complicated, but basically it produces a couple of different common types of tides. The simplest one is a **semidiurnal tide**, which is a tide that comes in and out a few times per day and has about equal dimension for the high tides and low tides.

- The more common tide is called a **mixed tide**, which comes in 2 times per day—but in nonequivalent size. There are mixed tides in many places around the planet that include a higher high tide and a lower high tide each day, and the same for the low tides.

- There are other places—especially those that are around large but still confined ocean basins—that have **diurnal tides**, which only come in once per day instead of twice per day.

Amphidromic Circulation

- The term amphidromic refers to an area where the tide sweeps around in some way. An amphidromic point is a no-tide location in the ocean—a node in a tide wave.

- **Amphidromic circulation** is the rotational motion of a tide through any kind of circular U-shaped, or even roughly U-shaped, basin.

- The Coriolis effect deflects water motion in ocean basins because of the rotation of Earth so that the tide wave tends to rotate around amphidromic points.

- The water that's entering any basin in the Northern Hemisphere deflects in a counterclockwise way. In the Southern Hemisphere, it turns in a clockwise rotation.

- Macrotidal areas are places that have especially large tidal range. Confined basins in areas that have the appropriate geometry for the tidal water that's rushing in to be funneled and concentrated into shallower and shallower water over a smaller and smaller area are regions that are good candidates for becoming macrotidal.

- The net effect of the dynamic theory of tides and the complexities of the coastline and of the amphidromic circulation is that the tides vary a lot from place to place. Tidal prediction is based on these equilibrium and dynamic theories of tides. It's also calibrated to the local history in any given spot.

- A **tidal bore** occurs when the tide rushes in with a flood current, but because it's entering a very confined channel, the water can't rush any faster than a certain speed, so the tide piles up on itself and builds a forced wave that's like a surge of water.

- Tidal water motion causes friction, generating heat, and dissipates the energy of Earth's rotation: Tides are slowing Earth down. The day is getting longer by about 2.3 milliseconds for every century that goes by.

Important Terms

amphidromic circulation: Tidal movements as affected by Coriolis forces, causing high water to circulate around a node, or no-tide point.

diurnal tide: A single daily cycle of one high and one low tide.

mixed tide: Most common type of daily tide cycle, exhibiting 2 tidal cycles per day with differing highs and lows.

neap tide: The relatively small range between high and low tide at times of quarter Moon due to destructive interference of solar and lunar gravity.

semidiurnal tide: A daily cycle of 2 high and 2 low tides.

spring tide: The relatively large range between low and high tide at times of constructive interference of lunar and solar gravity during full and new moons.

tidal bore: An inrushing high-tide wave that funnels up a confined river or estuary.

Suggested Reading

Cartwright, *Tides*.

Pugh, *Changing Sea Levels*.

Questions to Consider

1. Do you think there would be tides in bodies of water besides the ocean, such as the Great Lakes?

2. Why do we call Laplace's improvement on the equilibrium theory of tides "dynamic"?

Marine Life, Energy, and Food Webs

Lecture 17

Storage and use of energy is the distinguishing factor of all living things, including the vast diversity of life in the ocean. Life first emerged in an oceanic environment about 4 billion years ago and, for the majority of all time, existed and evolved only in the ocean. All life on Earth can be divided into primary producers and consumers. Trophic pyramids and food webs are ways to understand the complex feeding and energy relationships among members of a marine biological community.

Life on Earth

- Life is capable of organizing energy—that is, capturing it, storing it, and putting it to use to continue to live in a particular habitat and, ultimately, to reproduce itself.

- The directed use of energy that defines life counters entropy and the second law of thermodynamics, which states that all energy goes from states of being more ordered or concentrated to less ordered or concentrated. Life works against that principle by concentrating energy and using it to make a living.

- All life we know about is based on carbon and uses very specific molecules of carbon: RNA and DNA. Life seems to have come from a common origin on Earth.

- All life requires water. We know that life must have evolved in the ocean and the fact that all life uses the same fundamental metabolic tools suggest that life evolved only once on this planet.

- Earth holds perhaps 100 million different species, but they all have these common roots.

Living Systems

- Virtually everything is dependent on a chain of primary producers and consumers. The primary producers are the organisms that can produce food—or at least carbohydrates and sugars that are carbon compounds that store energy originating from somewhere outside of life.

- Most of the primary producers use light to generate energy through the process of photosynthesis, but some use chemical energy from Earth to use in the process of **chemosynthesis**.

- All of that energy flows from the Sun into the sea by primary producers as photosynthesizers, which turn carbon into something that can be used as chemical fuel or food. This food is very often consumed by other organisms who depend on the primary producers to make the food.

- Ultimately, energy flows through living systems: It starts as light energy, flows through as chemical energy, and ends up dissipated as heat—where it warms the ocean or the atmosphere and radiates into space.

- **Primary production** is defined as the synthesis of organic materials from inorganic substances by either photosynthesis or chemosynthesis. Most of the primary production on the planet occurs through photosynthesis. Chemosynthesis occurs by bacteria and simpler organisms called archaea.

- Productivity is measured in terms of the amount of carbon that's fixed or bound into organic material, organic compounds, and all the material that makes up our bodies and the bodies of organisms in the ocean.

- In the ocean, photosynthesis is conducted primarily by phytoplankton, by different kinds of photosynthetic bacteria, and by marine plants and seaweeds.

- Photosynthesis is carried out by the action of chlorophylls, or other compounds that plants, animals, and bacteria can use to create more complex hydrogen and oxygen compounds from the energy from sunlight. Organisms that can make their own food through primary production are called **autotrophs**.



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A copepod is a tiny crustacean that grazes on phytoplankton and is the most abundant animal on Earth.

- The major oceanic primary producers include phytoplankton, cyanobacteria, seaweeds, and vascular plants such as sea grasses and mangrove trees. All primary producers use a form of chlorophyll to turn solar energy into carbohydrates.

- The producers fuel, or feed, the consumers. The consumers are also called **heterotrophs**, which are in opposition to autotrophs because they cannot make food themselves. Instead, heterotrophs obtain food by consuming the primary producers themselves or the carbohydrates they generating.

- A process called **respiration** counterbalances photosynthesis. Respiration, in the biological sense, uses the carbohydrates—breaks them down with oxygen and obtains the stored chemical energy they hold—releasing carbon dioxide into the environment as well as releasing a certain amount of water.

Measuring Primary Production

- In general, primary production is the fixation of carbon. It is measured in terms of the grams of carbon per unit of mass or area of the ocean. We think about in terms of what the biomass is that's generated by fixing carbon, and we can measure it by weighing biomass or by coming up with a cumulative mass of living tissue over a certain interval of time or in a certain region.

- Primary production in the marine setting is 35 to 50 billion metric tons per year. In other words, that is the total biomass generated in a given year in the ocean environment. On land, it's 50 to 70 billion metric tons—roughly comparable.

- The total amount of actual biomass that's cumulatively present in the ocean at any given time is about 1.2 billion metric tons, whereas on land it's 600–1000 billion metric tons. There's much more biomass on land because land organisms tend to store biomass.

- When oceanic primary producers fix carbon, it's very quickly consumed, and those consumers are often very quickly consumed themselves. Life cycles are very short. The ocean is cranking out biological material at a prodigious rate compared to land, which tends to store it up over longer intervals of time.

- Some ocean environments are much more productive than others. Areas around the coastline are highly productive environments. The open ocean, by contrast, is a relative biological desert.

- About 1/2 the productivity of the ocean is in the coastal ocean, and the other 1/2 is in the upwelling regions—where deep, cold water comes to the surface—but only about 1% is in the open ocean, even though the area of the ocean is 81.5% open ocean and only 18% coastal regions. The upwelling areas comprise less than 1% of the ocean.

- Upwelling areas are areas of high productivity because nutrients are available to organisms that also have a lot of sunlight—the 2 ingredients that are needed and are limiting factors.

Trophic Levels and Food Webs

- An organism's **trophic level** is how far removed it is from primary production. The primary producers are the base of the trophic pyramid—the first trophic level. The consumers that eat the primary producers are first-level consumers, and then there are second-level consumers that eat the first-level consumers, and so on.

- The amount of biomass it takes to consume keeps building in an exponential way to get the same amount of biomass at the next trophic level. For each jump in trophic level, there is approximately a tenfold change in mass.

- A **food web** is a diagram that illustrates the feeding relationships and, therefore, the flow of energy through various biological communities. The web has arrows showing consumption connections from all different kinds of trophic levels; these arrows show the direction of energy flow.

- One organism can be at not just one trophic level, but—depending on what it's feeding on and perhaps even depending on the season—it could be eating at multiple trophic levels within a system.

- There are some physical and chemical factors that govern the productivity of life. The first one is access to energy, which comes in 2 forms: light, which can be used to make food, and temperature, which is needed by organisms in the form of heat to maintain metabolic processes.

- The other important factor that governs productivity is nutrients. Organisms need a variety of chemical nutrients to be the building blocks of the carbohydrates that are made as part of the process of metabolism.

- The chemical environment is important for maintaining cellular structure. Some chemical factors are salinity, dissolved gases—such as oxygen and carbon dioxide—pH, and water pressure.

- Any of these chemical factors can be a limiting factor, which is a factor whose presence and available amount governs the amount of productivity, or the amount of biomass that can be generated.

Oceanic Productivity

- There are some very important limiting factors that govern oceanic productivity, such as light, and the photic zone is consequently divided into a euphotic zone and a disphotic zone.

- The **euphotic zone** is located about 20 to 70 meters below the surface of the ocean and is the uppermost part of the photic zone where phytoplankton capture more energy than they use to stay alive. This zone composes less than 1% of the total ocean volume.

- The **disphotic zone** is located about 70 to 600 meters below the surface of the ocean and is the area of the photic zone where light is present but cannot support net energy gain through photosynthesis.

- In the aphotic zone, there is no light. There is perpetual darkness below 600 meters of depth or less. Most of the ocean volume is completely dark.

- Temperature governs the metabolic activity of organisms and the solubility of gases in water and rates of evaporation (sea-surface salinities). The metabolic rate is defined as how fast energy-using reactions can proceed in an organism.

- Temperature in ocean waters varies from near freezing—below 0°C, or 32°F, in deep saline polar regions—to as high as 40°C, or 104°F, in shallow tropical lagoons.

- Hydrothermal vents produce water at up to 400°C, but living microbes seem to edge up to them, with a limit of 121°C or less—as far as we know.

- Gases are more soluble the colder the water is. Cold water has a lot of gases that are nutrients whereas warm water is relatively depleted in these gases.

The Nutrient Cycle

- Phosphorus in the form of phosphates, nitrogen that is fixed in the form of nitrates, and trace metals—such as iron—are all key chemical nutrients that organisms need to live. The key nutrients that are used in the ocean are similar to those that are needed on land.

- Nutrients tend to be recycled through biological materials, meaning that the organisms that have them extract them from water. The nutrients are relatively scarce when organisms die, but then decomposers decompose the bodies of organisms and rerelease those same nutrients that are quickly scavenged up by other organisms to be used again.

- The nutrient cycle has a lot to do with the cycle of growth, death, and decomposition of individual organisms, which means that nutrients have to cycle and diffuse through water in different ways.

- Nutrients that are recycled through decomposition, which mostly occurs at the depths of the ocean, have a barrier in certain waters to make it back up to the surface.

- If there's a strong thermocline or pycnocline, water doesn't easily circulate between the surface water and the deep water, causing the nutrients to diffuse through the water across the stratified layer that is represented by the thermocline and pycnocline.

- Oxygen and carbon dioxide are limiting factors, and they also vary a lot with depth. Oxygen is abundant near the surface due to photosynthesis. Respiration of heterotrophs creates an **oxygen-minimum zone**, and then it is more abundant again in cold, deep waters. Carbon dioxide is the opposite.

- Organisms also need the ability to deal with salinity. Cells have to control their chemical environment through the processes of **diffusion**, **osmosis**, and **active transport**. The medium around a cell is isotonic or hypertonic.

- Isotonic means the cells have the same salinity as the solution outside the cells. The cells are able to maintain their shape, and there's no osmotic pressure across the cell to move water back and forth across that boundary.

- If cells become hypertonic, then water wants to move out of the cells, so they tend to shrivel up. The salinity is higher inside the cells, and water tends to come in and blow the cells up.

Important Terms

active transport: A process by which cells use energy to move solutes against the concentration gradient across membranes.

autotroph: Any organism that produces carbohydrate food from primary sources of energy.

chemosynthesis: Production of carbohydrate food energy by extraction from the breaking of chemical bonds.

diffusion: The spreading and dilution of solutes by movement from areas of higher concentration to lower concentration.

disphotic zone: The region of the water column in which light is present but insufficient for photosynthesis.

euphotic zone: The uppermost portion of the photic zone with sufficient sunlight for net gain in energy through photosynthesis.

food web: Representation of the feeding relationships and flow of energy through a biological community.

heterotroph: Any organism that consumes organic matter produced by others.

osmosis: A passive process causing net movement of solvent (water) across a membrane separating 2 solutions of different concentration level, tending to equalize their concentration.

oxygen-minimum zone: Depth range in the ocean where available oxygen is lowest, beneath the photic zone but above the cold, very deep waters.

primary production: The creation of biomass through photosynthesis or chemosynthesis.

respiration: Metabolic process of consuming energy by breakdown of carbohydrates with oxygen to fuel activity, releasing carbon dioxide.

trophic level: A scale of how many steps of consumption an organism is removed from primary production.

Suggested Reading

Miller, *Biological Oceanography*.

Morrissey and Sumich, *Introduction to the Biology of Marine Life*.

Questions to Consider

1. The open ocean is not very productive; it's said to be a biological desert. What limiting factors might govern that?

2. Primary producers and organisms that respire each provide something the other needs (e.g., oxygen and carbon dioxide). Which do you suppose came first, or did they perhaps arise together in synergy?

Tiny Plankton—The Most Abundant Life on Earth

Lecture 18

Floating microscopic plankton, comprising a wide range of both plantlike organisms and animals, are the foundation of the marine food web and are the most abundant life on the planet. Phytoplankton (diatoms, for example) are the green plants of the sea, the autotrophs that live in the sunlit photic zone. Zooplankton (krill, for example) are the animals that primarily float rather than swim and range from microscopic to giant jellyfish. The single most abundant and wide-ranging animal on Earth is the copepod, a tiny crustacean that grazes on the phytoplankton.

Plankton

- **Plankton** are the most abundant life on the planet. They are floating microscopic organisms of various types and are comprised of both plantlike organisms and animals. Plankton are the foundation of the marine food web.

- Anything that lives in the pelagic environment is living suspended in the water. There are 2 fundamental categories of pelagic life: nekton, the organisms that actively move around by swimming through the water, and plankton, organisms that drift or propel themselves only in a very limited way.

- There are microscopic plankton, but plankton can also be macroscopic organisms, or large-scale creatures, as large as 8-meter-long jellyfish. All types of plankton, however, drift with the motions of the water and have specific habitat requirements related to staying within the well-lit euphotic zone.

Types of Plankton and Common Characteristics

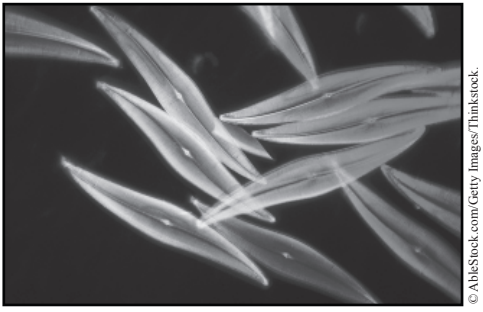
- Phytoplankton are the microscopic, single-celled, photosynthetic organisms—mostly algae—that are primary producers. Examples include diatoms, dinoflagellates, and coccolithophorids.

- Zooplankton are small animals, often microscopic in size, that are primary consumers that generally graze on phytoplankton. Examples include krill, jellyfish, copepods, and ctenophores.

- Zooplankton also include single-celled protistans, or protist organisms. They're still grazers and consumers, but they're single-celled organisms. Examples include radiolarians and foraminifers.

- Bacterioplankton include both the autotrophic cyanobacteria and the heterotrophic decomposer bacteria that break down the organisms that have died and have fallen through the water to the bottom of the ocean.

- Meroplankton are the larval stages of some of the other animals, the nektonic and benthic organisms, that live in the sea. These include the larval stages of corals and of many fish and crabs.



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Phytoplankton are microscopic, single-celled, photosynthetic organisms that are primary producers.

- Plankton represent all the different domains of life on Earth, from the simplest prokaryotic organisms—the single-celled bacteria and archaea—to the more complex organisms that diverged from the bacteria and archaea.

- The shallow, near-surface euphotic zone is the habitat of the primary producers that represent much of the plankton as well as the primary consumers that graze directly on those organisms.

- Phytoplankton need to stay where the sunlight is available for photosynthesis. They can't swim through the water, yet they still need to be able to remain in the photic zone.

- Most organisms, including single-celled organisms and phytoplankton, have bodies that tend to be negatively buoyant, which means they tend to sink through still water.

- Phytoplankton use several adaptations to remain in the photic zone. One is to be as close to neutral buoyancy as possible, meaning the density within the organism should be as close to the seawater around it as is possible.

- To achieve neutral buoyancy, phytoplankton can minimize the amount of heavy material that they have by secreting oil droplets, or small pieces of fatty acids, which are less dense than water. They maintain those oil droplets either on or within their protoplasm, cell walls, or bodies.

- In addition, a large surface-area-to-volume ratio is important to prevent sinking through the water. Having a tiny size increases that ratio, and having a complicated body shape—lots of spines or appendages sticking out from the body—increases surface area and slows down the sinking process.

- Furthermore, plankton can maintain their position in the water column by having a flat shape or by making colonial chains with similar organisms. Also, even single-celled organisms can have propellers, flagella, or cilia, which are used to beat in the water and propel themselves short distances.

Sampling Plankton

- The fundamental method that biological oceanographers and marine biologists use to sample plankton hasn't changed much since the 19th-century *Meteor* and *Challenger* expeditions, which pioneered the use of the plankton net—a very fine-meshed, conical, narrow, windsock-shaped net with a special cup at the base that is towed through the water on a cable.

- The concentration of the plankton in the net divided by the amount of water the cup was passed through gives a density of the plankton at a particular depth. One disadvantage of a plankton net is that it only catches the organisms in the water that are large enough to be caught in a mesh net of that size.

- Both phytoplankton and zooplankton are ubiquitous and are present in the water in large numbers, depending on the productivity of a particular zone.

- Phytoplankton are a vast but incredible biomass in the global euphotic zone that makes 40% of all photosynthetic production on Earth—far more than seaweeds.

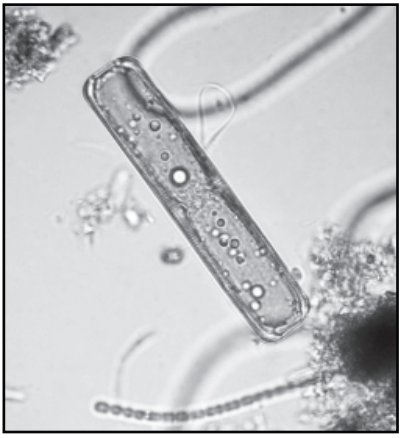
Types of Phytoplankton

- There are 8 major types of phytoplankton, but the main 3 are the diatoms, dinoflagellates, and coccolithophorids.

- **Diatoms** are the most productive of phytoplankton; they are single-celled algae that make a transparent silica-glass shell called a frustule. These transparent shells are often very complex geometric structures that are made of 2 halves or valves that fit together like a hat box.

- Frustules provide protection for the protoplasm of the organism, which includes chloroplasts, or cellular bodies that have chlorophyll in them. These shells also let light in so that photosynthesis can be efficient.

- Diatoms are the most efficient photosynthesizers on the planet. They can convert as much as 80% of the incoming sunlight directly into chemical energy. They store that energy in the form of food as fatty acids and oils, which provide them with carbohydrates and help with buoyancy.



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Diatoms are single-celled algae that make transparent silica-glass shells that are very complex and beautiful.

- The second type of single-celled autotroph is a **dinoflagellate**, another silica-based organism. Dinoflagellates have 2 whiplike flagella, which are small appendages that can be rotated by the organism to move it upward or downward relative to the sunlight.

- Plankton have the ability, like most single-celled organisms, to very rapidly reproduce, which leads to geometric expansion if limiting nutrients and sunlight are available. If the conditions are favorable, they will divide and double in as little as 12 to 24 hours through asexual reproduction.

- Some dinoflagellates produce very strong neurotoxins—direct metabolic products—that affect marine organisms and the human beings who eat them.

- Red tide is considered to be an HAB, or a harmful algal bloom. Red tide is a massive bloom of millions of dinoflagellates per gallon of water that turn the water or the shoreline bright red and is completely unsafe for consumption and even respiration.

- A third type of phytoplankton is **coccolithophorids**, the calcareous phytoplankton. The most common coccolithophorid is a single organism called *Emiliania huxleyi*, which is tremendously productive and ubiquitous in the ocean. This microscopic organism has a cytoplasm that includes platelets made of calcium carbonate that form calcareous ooze deposits and chalky rock after the organism dies.

- Satellite imagery shows high productivity of phytoplankton in northern and southern oceans during the summertime. Productivity drops to basically zero during the wintertime. The tropics don't change much, but the coastal regions have greater spring and fall productivity and relatively less productivity in the summertime than in the wintertime.

Photosynthetic Picoplankton and the Microbial Loop

- Photosynthetic picoplankton, which are only 0.2 to 2 microns in size, were not even discovered until the early 1980s through flow cytometry at sea and other advanced methods of DNA detection. However, they are perhaps the most abundant bacteria on the planet: There are 100 million of them in every liter of seawater on Earth.

- The *Prochlorococcus* are amazing light scavengers. They live very deep in the dysphotic zone, in which only 0.1% of the surface light penetrates. Most of these organisms can't make a living by photosynthesizing at such depths.

- All the activity of these organisms—as well as other related cyanobacteria—fuels a food web known as the **microbial loop** because it is largely independent of the main marine food chain, but it's a key component of that food chain.

Types of Zooplankton

- Zooplankton can be broken down into 2 categories: holoplankton, which are organisms that spend their whole lives as plankton, and meroplankton, which are juvenile forms of other organisms—such as crabs, barnacles, and clams—that only spend a portion of their lives as plankton.

- A **copepod** is a crustacean; all copepods are invertebrates and microscopic. Copepods are the most abundant animal on Earth. They're ubiquitous throughout both shallow and deep ocean water.

- **Krill** are related to shrimp but are smaller in size. They are arthropods, but they are also crustaceans like the copepods. Krill are tremendously productive seasonally, especially in the waters off Antarctica; they are the base of the high-latitude food chain.



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Baleen whales predominantly feed on krill, which form the basis of the food chain for various organisms.

- A foraminifer, or foram, is an organism that is similar to an amoeba and looks like a phytoplankton but is actually a single-celled animal. Forams consume phytoplankton and even other zooplankton, such as copepods. Forams build tests, or skeletal structures, that have many delicate spines that stick off in order to hold it in the water.

- Even in the 21st century, it seems like virtually every expedition to sea to look at plankton as a species makes new discoveries that are rapidly advancing our understanding of the abundance, energy, and food systems that plankton are the basis of for the entire ocean.

Important Terms

coccolithophorid: An abundant group of calcareous algal phytoplankton; their remains are responsible for chalk.

copepod: Very small crustacean zooplankton that are widespread in the pelagic ocean.

diatom: A major and abundant group of siliceous single-celled phytoplankton; they produce glassy frustules.

dinoflagellate: A major and abundant group of siliceous single-celled phytoplankton; they have whip-like flagella.

krill: Crustacean zooplankton, very abundant in Antarctic waters in particular.

microbial loop: A producer-consumer food web in the ocean consisting entirely of bacteria and largely independent of the conventional ecosystem.

plankton: All organisms that drift with water movements and currents passively.

Suggested Reading

Miller, *Biological Oceanography*.

Morrissey and Sumich, *Introduction to the Biology of Marine Life*.

Questions to Consider

1. What would oceanic food webs be like if there were no phytoplankton at all?

2. Plankton have evolved greatly over time, despite their apparent simplicity. What oceanic factors might pressure them to do so?

Soft-Bodied Life in the Dark, Open Depths

Lecture 19

The vast volume of the open ocean is the pelagic zone, dimly lit and very poorly understood until recently. Beneath the sunlit euphotic zone, the dark water mass supports a diverse ecosystem of pelagic organisms, many of which have no hard parts to their bodies and are virtually transparent. Until submersibles became available, these organisms were almost entirely unknown to science. The basis of the pelagic food web is mainly detritus raining down from surface waters. In the darkness, bioluminescence is an important means of both attracting prey and confusing predators.

Life in the Deep Pelagic

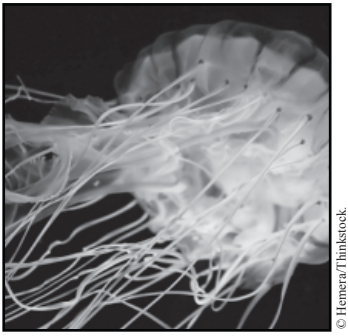
- A great deal of life in the ocean, from the surface to great depths, is composed of organisms with no hard parts on their bodies. Except for the surface dwellers, these organisms were barely known to science until recent decades because they are difficult to sample and leave only a small trace in the form of sediments or fossils.

- Below the pelagic photic zone and the pelagic euphotic zone in the open-ocean environment—from about 200 down to 1000 meters—is a region that oceanographers call the **mesopelagic zone**, the middle pelagic zone. This is the transitional region that's disphotic in terms of light and is sometimes called the twilight zone.

- From 1000 meters all the way down to just above the bottom where the benthic realms exist is the deep pelagic, which is also called the bathypelagic or the abyssopelagic. This is the completely aphotic, or completely dark, deep water of the ocean.

- The most familiar of the gelatinous organisms, the jellyfish, are in a phylum of organisms called Cnidaria—the same phylum as sessile organisms, which live on the bottom of the ocean and stay in one place like anemones and corals.

- All Cnidaria have stinging cells called cnidocytes, which are sometimes called **nematocysts**. They also share a symmetrical body plan with a simple, single orifice that is used for both the intake of food and the expulsion of wastes. Cnidaria are largely carnivorous, and they generally eat crustaceans and fish.



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A jellyfish is a single organism that is multicellular and has specialized cells that create the head and carapace, for example.

- A jellyfish is a single organism that is multicellular and has specialized cells. For example, the head, or carapace, of a jellyfish is made of a material called **mesoglea**, which is the jellylike substance secreted by the organism that helps it float.

- Cnidocytes, or nematocysts, are the tiny, toxin-containing harpoons that Cnidaria have. They are subcellular structures that are used to capture and stun or kill prey.

- Jellyfish stings vary from being mild to deadly. Box jellyfish called the sea wasp inhabits waters near Australia and is perhaps the most lethal of jellies to humans.

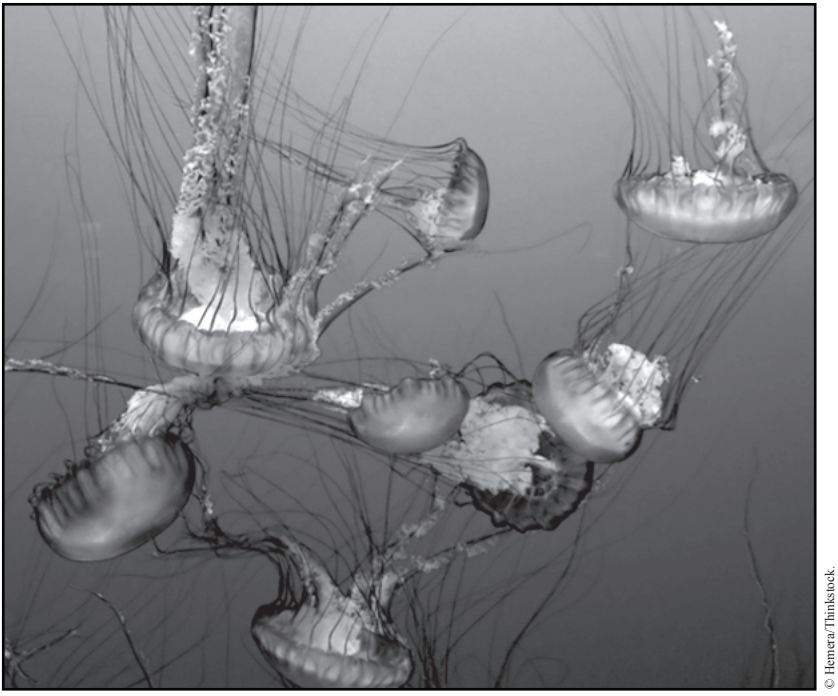
Types of Jellylike Organisms

- There is a vast array of jellylike organisms besides the true jellyfish, and many have only recently been discovered or understood by biology in any significant way.

- **Siphonophores** are closely related to the true jellyfish. They are also Cnidaria, but they're a colonial invertebrate organism. Jellyfish do not self-propel in any organized sense, but siphonophores do.

- Siphonophores are made up of individual, separate organisms—called zooids. They're so tightly symbiotic that they cannot live independently from one another.

- Within one siphonophore colony, there's a central stem and 2 types of zooids: the nectophores, which are the propulsion but can't consume food, and the polyps, which can't swim but can feed. The nectophores are similar to jellyfish; the polyps are similar to anemones.



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The pulsing motion a jellyfish makes is not so much for propulsion as for sweeping water, along with food particles, toward the mouth.

- All siphonophores have this same strange body plan: The nectophores and polyps bud from the same organism along a central organizing stem. They also all have the ability to coordinate swimming and feeding. Perhaps these organisms provide a clue to how chordates and vertebrates first evolved.

- The Portuguese man-of-war is not an ordinary jellyfish but a siphonophore colony, too. This organism is found mainly in tropical waters and is a true plankton in the sense that it is a drifter—despite its large size.

- Another type of jelly is a **ctenophore**, which is also known as a comb jelly and sometimes colloquially as a sea walnut. Ctenophores have a jellylike, no-hard-parts structure, but they are not in the Cnidaria. They have no stingers, but they do have cilia on some of their cells that slowly propel them through the water.

- Another type of jelly is a **salp**, which is a colony of simple chordates called tunicates. It's not Cnidaria, but it's not like a siphonophore either. They form long chains, but they can live individually as well. They feed largely on phytoplankton.

- One more unusual jellylike creature is called a pteropod, which is a mollusk—closely related to such organisms as snails and slugs. Most pteropods don't have shells, but they all have a single pod, or foot, that gives them their name and propels them through the water.

Submersibles in the Deep Pelagic

- Many newly discovered vertebrate and invertebrate organisms—as well as highly specialized fish such as anglerfish, viperfish, and saccopharynx—populate this world in a surprising diversity.

- Until true deep-submergence vehicles, or submersibles, became available to science beginning in the 1960s, the deep pelagic life was almost entirely unknown to science—except what little had been discovered by dragging plankton nets through the water.

- Deep submersibles became available to science with the development of the submarine *Alvin*, which went into operation in 1964 and was the first submarine available for deep diving to beyond hundreds of feet to thousands of feet in the ocean. The original *Alvin* is still in operation today.

- There are other deep submergence vehicles in the world too, but not very many. There's a French submersible called *Nautile*, and there are 2 Russian submersibles, *MIR 1* and *MIR 2*. There's a Japanese submersible called *Shinkai 6500*, which is the deepest-diving manned submersible in the world.

- The *Johnson SeaLink II* can reach a depth of about 900 meters and has been one of the vehicles that has photographed and sampled many of the organisms in the mesopelagic zone.

- Modern work is increasingly being carried out by remotely operated vehicles (ROVs), or so-called robot subs, than with submarines carrying people to the ocean floor. They're much less expensive and, in fact, less dangerous to operate.

- The trend in science, as well as in offshore petroleum industries, is to use ROVs in much larger numbers. Examples of ROVs used for scientific research are Jason, which is operated by the Woods Hole Oceanographic Institute, and Ventana, which is operated by the Monterey Bay Aquarium Research Institute.

- ROVs, among many other oceanographic tools, played a huge role in what was called the Census of Marine Life, a decade-long, $650 million global research effort that lasted from 2000 to 2010. Approximately 2700 scientists went on 540 expeditions, during which more than 6000 new species were discovered, including entirely new ecosystems and communities.

- About 250,000 marine species were confirmed—excluding microbes—but there are probably 750,000 more that remain to be described. In addition, it is estimated that 1 billion types of microbes exist in the ocean.

The Deep Pelagic Food Web

- At the surface of the ocean, phytoplankton form the base of the food web. Zooplankton feed directly on the phytoplankton, and various higher-trophic-level consumers feed on zooplankton, or directly on phytoplankton—or both—and build up the familiar food webs.

- In the deep pelagic zone, there is no photosynthesis and, therefore, no phytoplankton. The basis of the food web in the deep pelagic is mainly detritus raining down from the surface waters and filtering down through the water and then being scavenged up by various organisms.

- A few examples of such scavengers are copepods and amphipods (in the same family as krill). These 2 types of zooplankton are the new mainstays of the food web in the deep pelagic because they scoop up detritus and then are eaten by larger organisms like fish.

- There are deep pelagic nekton, which are active swimmers that consume detritus scavengers in the deep pelagic. They include numerous species of cephalopods, which have a head that's divided into a number of tentacles.

- For the most part, these cephalopods, or mollusks, are different kinds of squid. Squid swim in groups and prey on small fish. Mesopelagic squid are transparent and are nearly jellylike cephalopods.

- The deep pelagic zone also includes some of the largest invertebrates that live on the planet in the form of giant squids and even what are called colossal squids. Giant squids stay in the deep zone and never come anywhere near the surface.

- Deep pelagic organisms have some interesting adaptations to the water depth. For example, many of them are colored a deep red. No red light penetrates that deep, so any red animal actually appears to be black even in the partially photic zone.

- Deep pelagic fish feed on copepods, krill, and other small fish. Deep pelagic fish are some of the strangest forms that we see on the planet, but they share some common characteristics.

- In the deep pelagic zone, the fish tend to be small because there's not a lot to live on. They also tend to have very large mouths and needlelike teeth. Many of them barely swim; instead, they keep their metabolism low and wait to lure prey.

- In fact, many of these fish use a specific adaptation called **bioluminescence**, which is the ability to generate light, and special organs called **photophores** to lure prey. Anglerfish and lanternfish use photophores as lures. These fish look scary until you realize how tiny they are.

- In the disphotic and aphotic zone, bioluminescence is an important mechanism for survival. The purposes of bioluminescence are to communicate with one's own species, to confuse predators and as a form of camouflage, and to attract prey.

- There are a wide variety of microbes, invertebrates, and fish that produce bioluminescence, which is created by a chemical reaction called chemiluminescence, the combination of the vividly named enzymes luciferin and luciferase.

Important Terms

bioluminescence: The process of production of light by an organism, used for camouflage, defense, and attraction of prey and mates.

ctenophore: Very common pelagic gelatinous organism, also known as comb jellies.

mesoglea: Translucent, jellylike gel that makes up the bulk of organisms like jellyfish.

mesopelagic zone: The dimly lit region of the water column; also called the disphotic zone or the twilight zone.

nematocysts: Also known as cnidocytes, the stinging cells of many jellyfish and other cnidarians.

photophores: The organs that produce light in bioluminescent organisms.

salp: A tubular, gelatinous animal that lives either as an individual or as a colony that is common in equatorial waters.

siphonophore: An order of Cnidaria that are colonial animals; one example is the Portuguese man-of-war.

Suggested Reading

Nouvian, *The Deep*.

Prager, *Sex, Drugs, and Sea Slime*.

Questions to Consider

1. Do you think a colonial organism like a siphonophore is one animal or a community working together? How about an ant colony? Or the collection of cells that make up a dolphin? What basis do you use to draw a distinction?

2. How many different uses can you list for bioluminescence in organisms that live in the aphotic zone?

Swimming—The Many Fish in the Sea

Lecture 20

Nekton are all the actively swimming organisms in the ocean, ranging from fish to invertebrates to mammals and birds; nekton have evolved many specific adaptations to succeed in their marine habitats. Squid, octopus, and nautilus are mollusks, which are invertebrates with remarkable adaptations and apparent intelligence. The most successful nekton families are the bony fish, which are uniquely well adapted to their environment—particularly through having evolved the oxygen exchange system of gills.

Active Swimmers

- There are certain characteristics that are shared by most of the marine organisms that are rapid or powerful swimmers. Those basic functions are streamlined in shape and energy efficient, effective propulsion.

- From car and airplane-wing design, we know that a teardrop shape is aerodynamic. It's the shape that in a wind tunnel produces the least drag and the least turbulence.

- A phenomenon called vortex shedding involves the creation of vortices, which take some of the energy out of the flow, behind an object embedded in a streaming fluid. It's a fundamental problem of turbulence and drag in flow in any medium. The teardrop shape inhibits vortex shedding.

- Water is much thicker and more viscous than air, so it is extremely important to minimize drag in water because drag in water is many times greater than drag in air.

- There are certain body shapes for organisms that do the best job of minimizing drag. Drag is minimized when the ratio of the width to the length in terms of the profile, or cross-section, of a given body moving through liquid is about 0.2 to 0.25.

- The body shapes that have been evolved by many different marine organisms come very close to the mathematical calculation of what the optimal body plan is. Organisms like swordfish, tuna, and dolphins are at somewhere around 0.25 to 0.28, and they are the strongest swimmers in the sea as a result. The shape of a blue whale is very close to optimal at 0.21.

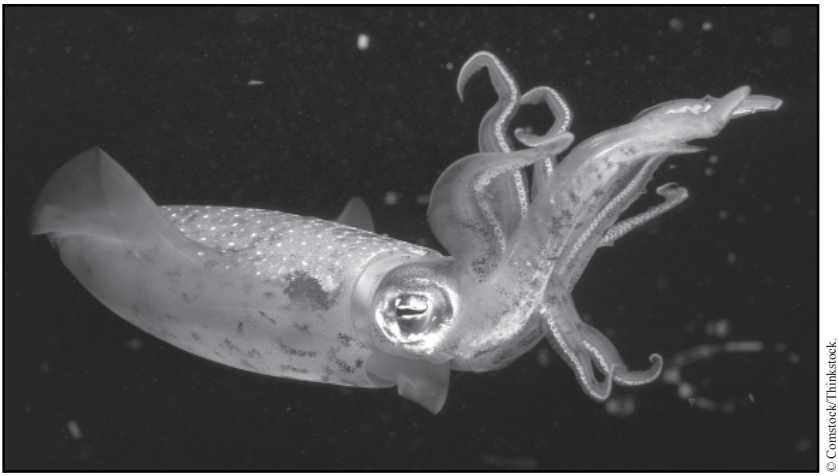
- In general, the different organisms that swim actively through the water provide an example of convergent evolution because these different organisms started out as very different types of creatures with very different types of body plans and, yet, evolved to these streamlined shapes.

- The hydrodynamic shapes all emerged from the ancient jawless fish, which evolved into some of the modern fish. A shark, for example, has a very streamlined shape, including fins that have evolved to control it and to enable it to swim in the water.

- In the ocean, the ichthyosaur—a marine reptile of the Mesozoic Era—evolved a similar shape, with a flipper system, from the legs of reptiles that evolved on land. In addition, the flippers of dolphins and whales evolved from land-based organisms that have legs. Birds such as penguins have evolved a flipper that was a wing that is currently useless for flight but is fantastic for swimming.

Categories of Active Swimmers: Invertebrates

- The category of active swimmers that is the most adapted over the longest period of time in the ocean is the invertebrates. The larger invertebrates, for the most part, are represented by the **cephalopods**—mollusks that actively swim. Cephalopods include squids, octopuses, and nautiluses.



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The ink that is produced by squids is used to confuse predators and prey as an escape mechanism.

- All cephalopods have a body plan that includes a single foot that protrudes directly off of the head of the organism and is divided into multiple parts, or tentacles. Cephalopods move around by jetting water from their bodies. They feed very efficiently by using their tentacles to capture prey, move it into their mouth, and then move it into their gut.

- The chambered nautilus is an interesting cephalopod because it makes a shell, which makes it look like a snail. It has a spiraling shell that is famous in both mythology and in the fossil record. These were very prevalent organisms in the Paleozoic Era before fish took over as the main organisms of the ocean.

Categories of Active Swimmers: Vertebrates

- The most numerous species of **nekton** in the ocean, by far, are fish in terms of number of different species and overall adaptation success to all niches. In fact, fish are the most numerous vertebrates on the planet.

- There are 30,000 species (and still counting) of fish. There are more species of fish, in fact, and individuals of fish overall than all other vertebrates on the planet combined, including all the land vertebrates.

- Fish dominate the nekton because of the fact that they are adapted to virtually every niche in the ocean and virtually every habitat that's available in the ocean. Fish exist in all the zones of the ocean, but they are much more numerous in coastal areas and in surface waters of the ocean.

- There are a few distinguishing features that all fish have in common, including the existence of fins for various types of locomotion among several different species and the existence of gills for respiration.

- There are 3 major types of fish: jawless fish, cartilaginous fish, and bony fish. The cartilaginous fish are in the class **Chondrichthyes**, and the bony fish are in the class **Osteichthyes**.

- Cartilaginous fish are evolutionarily the oldest group of fish. They've been around for practically all of the 450 million years that fish have been on the planet. They evolved first in the ocean, before the bony fish did.

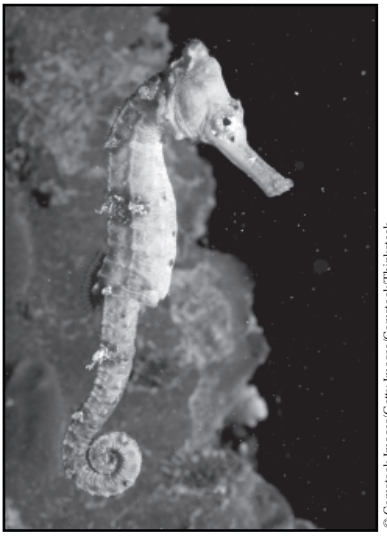
- The Chondrichthyes include rays, skates, and sharks. As the name cartilaginous implies, they have no true bone in their skeleton; they only have cartilage making up their skeletal materials. Their skeleton is fairly rigid, but it is more flexible than mineralized bone, which is what bony fish and other bony vertebrates, such as human beings, have.

- Even sharks' scales are basically cartilaginous. Shark teeth are modified scales that include dentine, a substance similar to what makes the teeth of human beings hard. All their scales have dentine, which is why they are so rough. Most sharks bear live young, which is different from bony fish but similar to mammals.

- Despite their relatively early evolution, sharks have developed some phenomenally acute senses, including some senses that are unfamiliar to humans.
    - Sharks have excellent vision, even in very dim light.
    - They also have a sense of smell and taste that's highly developed and includes their entire bodies.
    - Sharks have pit organs, which are chemical receptor cells that are distributed over their entire body.
    - They can also sense very weak electrical signals through a set of organs, which allows them to detect minute currents for use in orientation and predation.
- The vast majority of sharks have no interest in predation on human beings, and in fact, shark attacks are very rare. Great white sharks and mako sharks are the ones that can be dangerous to people. We are much more dangerous to sharks than they are to us because of overfishing and overconsumption.
- There are more than 450 species of Chondrichthyes, which include rays and skates. Most of them are basically benthic organisms, living near the sea floor in both shallow water and deep water.
- The largest Chondrichthyes are the manta rays, which are actually plankton feeders. Others are carnivorous and eat small seafloor organisms. Some have a tail with a barbed stinger, and others can produce electric shock—both of which are used as a defense against predators, not to intentionally cause harm.
- The bony fish are the most numerous fish by far. They evolved later than sharks and other cartilaginous fish, but they've radiated throughout the ocean and now represent at least 27,000 different species—probably with many more to be discovered.

- They're exquisitely well adapted for a wide range of marine habitats. Bony fish developed bony skeletons several hundred million years ago, and all land vertebrates evolved initially from bony fish.

- Examples of bony fish include salmon, tuna, halibut, flounder, herring, sea horses, and other familiar species.



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A sea horse, which is a type of bony fish, has a body plan that formed as a result of adaptation to its habitat.

Adaptations of Fish

- Bony fish have a variety of body shapes: Some are adapted in a streamlined torpedo shape for fast swimming while others are flat with a large dorsal area. In addition, others are laterally flat—thin looking but wide—for maneuverability in reefs, and many open-ocean fish are rounder to maintain buoyancy as they float along the surface.

- Some key adaptations of fish include having a streamlined in shape, propulsion, buoyancy (maintenance of level), gas exchange, osmoregulation (saltiness), and feeding and defense, which includes schooling behavior and bioluminescence.

- Fish are negatively buoyant and, therefore, sink; their bodies are denser than seawater, so they need to adapt. Cartilaginous fish have no specific adaptation to this except that they must remain in motion, so they glide as though they're in flight to maintain their height in the water. Their fins are like airplane wings.

- By contrast, most bony fish have **swim bladders** beneath their spinal column that are gas-filled chambers that can be delicately controlled to maintain neutral buoyancy. Abyssal species have developed oil-filled buoyancy chambers instead.

- A second adaptation is **osmoregulation**. All saltwater fish have body tissues that are less saline than the seawater around them, so they need to find strategies to maintain internal salinity. Because fish are hypotonic, they have the problem of constant water loss through their skin and scale structure. To offset that, fish are constantly excreting salt through their gills and even through their cells by active transport, forcing osmosis.

- Fish also need oxygen and need to expel carbon dioxide—just like humans do. Gills are the organs that they breathe with, and a gill is simply a way to put a very large surface area of a thin cellular membrane where their bloodstream can flow through gill membranes and exchange gases with dissolved oxygen in the water.

- Primitive fish like eels swim through the water in a sinuous motion, allowing them to swim like a snake crawls on the ground. However, this isn't a very efficient way to get around. By contrast, most bony fish have an inflexible and highly muscular body, which allows them to move straight while their tail moves back and forth.

- The schooling behavior of fish allows them to efficiently work together to appear much larger and, therefore, more intimidating to predators. The interesting things about a school of fish is that all the fish seem to turn as one. To carry out schooling behavior, fish have a lateral-line organ system, which includes pressure sensors that feel tiny motions in the water.

Important Terms

cephalopod: Mollusks including squid, octopus, cuttlefish, and nautilus that are characterized by bilateral symmetry, a prominent head exhibiting many tentacles.

Chondrichthyes: The taxonomic class comprised of all cartilaginous fish, such as sharks and skates.

nekton: All organisms that actively swim in the ocean (e.g., fish, marine mammals, cephalopods, and more).

osmoregulation: Biological process of controlling internal salinity and other chemical balances for optimum metabolism.

Osteichthyes: The taxonomic class comprised of all bony fish.

swim bladder: Gas-filled chambers many fish have beneath their spine to maintain buoyancy in the water.

Suggested Reading

Garrison, *Essentials of Oceanography*, chap. 14.

Videler, *Fish Swimming*.

Questions to Consider

1. Why don't biologists classify organisms by similar function of their anatomy rather than evolutionary lineage?

2. Does a fish's lateral-line system represent a true "sixth sense" compared to our familiar 5 or just a different application of one of them? What about the electrical signals that sharks can sense?

Marine Birds, Reptiles, and Mammals

Lecture 21

Perhaps the most intriguing of the open-ocean dwellers are the marine mammals: whales, dolphins, seals, sea lions, and manatees. Many spend all or most of their life in the open ocean. Marine mammals—Cetacea (whales and dolphins), Sirenia (manatees), and Carnivora (seals, sea lions, and walruses)—evolved from land-dwelling mammals and include the largest animals ever to have lived on Earth. Toothed whales use echolocation to find prey, and baleen whales—the largest of the animals—filter feed exclusively on some of the smallest zooplankton, krill.

Marine Birds

- We might not think of birds as marine organisms at all, but what they share with the marine reptiles and mammals is a total adaptation to the life at sea. The ones that we think of as true sea birds are birds that cannot live without the ocean as a large part of their habitat—for virtually everything except nesting.

- Seabirds run the spectrum of extremes in terms of flight from extreme fliers like albatross, who are adapted to fly long distances, to flightless birds like penguins, who are adapted to swim and feed exclusively under water.

- Flightlessness means that penguins can be very differently shaped from virtually all other birds: They can be large, which means they have a lot of fatty insulation and stubby appendages that keep them warm. They can also maintain neutral buoyancy by a combination of having fatty insulation as well as greasy feathers that are laden with insulating fat.

- Penguins are adapted to dive deep in the ocean with phenomenal ability. Emperor penguins, the largest of the penguins, are known to dive to depths of 265 meters and stay submerged for as long as 10 minutes or more.

- A few species of penguins really are almost entirely seabirds, spending 2 uninterrupted years at sea in between individual breeding episodes and then arriving on land or on ice shelves to breed.

Common Characteristics of Seabirds

- Most seabirds live in the Southern Hemisphere, which is also known as the ocean hemisphere because there's not much land and lots of very large areas of open ocean.

- There are a number of different types of seabirds. Gulls and pelicans are familiar shorebirds, and they exclusively feed on fish and invertebrates of the sea.

- The true seabirds are the pelagic birds called **tubenoses**, which include the albatross and sooty shearwaters that specifically travel across open areas of the ocean and are exquisitely good fliers.

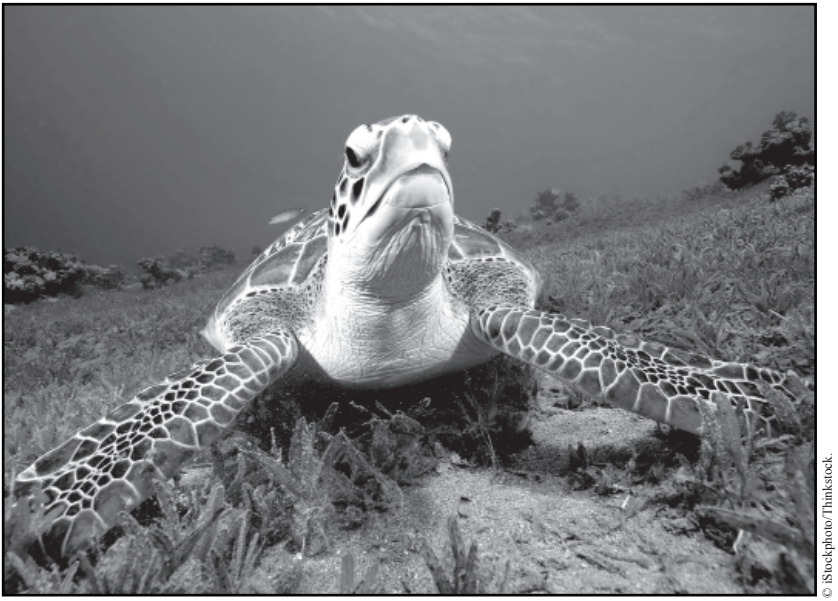
- All tubenoses share the ability, by way of the tube in their nose, to sample the airflow and tell them about their speed. These tubes also include special salt-excreting glands that concentrate the salt in their bodies—because they have no access to freshwater—and flow the brine out over their beaks.

- Virtually all marine birds live a fairly long time, have few offspring, and mate monogamously for life on remote rocks and islands where their nests are mostly undisturbed.

- The largest seabird is the wandering albatross of seafaring lore. They have wingspans of up to 3.6 meters (12 feet), yet they only weigh about 10 kilograms (22 pounds). They have a very delicate bone structure and an optimized wing shape for soaring: They barely flap their wings at all.

- One tagged albatross traveled 500 miles over the course of a day at an average speed of more than 35 miles per hour. They use the actual updrafts created by the rise and fall of the waves to keep them aloft.

- Wandering albatross only go ashore to breed on remote islands. They will spend many months at sea and bring food back to their offspring. They are able to find these remote locations because they have a magnetic sensing ability in their bodies that is similar to the capabilities sharks have.



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Sea turtles, like birds, come ashore to lay eggs, but they spend virtually all of their life history in the ocean.

- Another example of a tubenose is the sooty shearwater—a Southern Hemisphere bird as well. Sooty shearwaters are perhaps the most amazing long-distance fliers in the ocean. Tagged birds have been found to fly incredible distances—as much as 950 kilometers (500 miles) in a single day. They are not very large, but they can dive to great depths (68 meters or more) for fishing.

Marine Reptiles

- Related in some ways to birds through their common relationship to the dinosaurs and other even earlier organisms are the marine reptiles. Although reptiles are mostly land-dwelling organisms, each main group of present-day reptiles has some marine species: turtles, lizards and snakes, and crocodiles.



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As reptiles, lizards have evolved special salt glands that excrete excess salt from their bodies.

- All reptiles breathe air. None of them are aquatic in the sense of having gills, but they have special salt glands that excrete excess salt from their bodies—another example of convergent evolution.

- There are 8 different species of sea turtles. Like birds, they come ashore to lay eggs but at very infrequent intervals—such as every 2, 3, or 4 years. They spend virtually all of their lifetime in the ocean. In fact, sea turtles return to the original spot on the same beach that they were born on to lay eggs with an incredible sense of navigation.

- Sea turtles are a bit different from land-based turtles and tortoises. They can't retract their heads and limbs into their shell. The shell serves as protection from predators, but their fins are always out. They swim through the water with relatively slow, gentle propulsion.

- All of the major sea turtle species are threatened by human beings, and some are very much in danger. They all feed in shallow water on algae, sea grass, and plants, so they hug coastline areas and low-shelf regions where there is plenty of vegetative material for them to feed on.

Marine Mammals

- The 3 different groups of marine mammals are **Sirenia** (manatees and their relatives), Carnivora (seals and sea lions), and **Cetacea** (whales and dolphins). Each group evolved independently from land mammals that moved into the sea, and all have lost the ability to live totally on land.

- All of these are mammals, which implies that they have live young and feed them with milk. They all breathe air, so during the entire time spent at sea, they breathe air through their blowholes, nostrils, or other organs.

- All marine mammals have the streamlined body shape of high-energy, high-activity swimmers. They also have slippery skin or hair that has developed special oils to both retain heat and retain a slippery, smooth profile.

- All marine mammals are internally heated; they're warm-blooded organisms. They have to maintain a high endothermic body heat, so they need a high metabolic rate. Therefore, they need to consume a lot of food and burn a lot of food as well as be well insulated with fatty tissue. Their large size retains heat because they have a good surface-to-volume ratio.

- Marine mammals have unusual respiratory systems that efficiently use oxygen. Many of the marine mammals have special biochemistry that's optimized to retain and use oxygen during deep, prolonged dives.

- Gases collapse under high pressure, and marine mammals accommodate that by allowing their lungs to collapse after they've taken oxygen into their bloodstream—or while they're taking oxygen in. In fact, the pressure helps drive the dissolved oxygen into the bloodstream.

- Marine mammals also have very strong osmotic adaptations to living in salt water. There's little to no intake of seawater; they don't drink water for the most part. Instead, they get their freshwater directly from food tissue and also from the metabolism of carbohydrates.

Marine Mammals: Sirenia

- The manatees and the dugongs of Indonesia are virtually the only examples of Sirenia. There are only 4 species of these organisms on the planet, and all of them are herbivorous marine mammals—the only herbivorous ones.

- Sirenia graze on sea grass. They're closely related to the land-based grazers, including elephants and water buffalo. Calling them sea cows is not much of a stretch: They are organisms that have adapted to being in the water, so they have no legs. Both manatees and dugongs are currently endangered species.

- Steller sea cows have been extinct since 1768, but they were even larger than manatees—up to 30 feet in length and weighing 20,000 pounds. Seal hunters found them to be pretty easy pickings because they didn't move very fast, so they were hunted for their meat.

Marine Mammals: Carnivora

- The **pinnipeds** and **fissipeds** are of the order Carnivora, which include dogs, cats, bears, and weasels. The pinnipeds are the seals, sea lions, and walruses; the fissipeds are the sea otters. All of these are relatively recent arrivals in an evolutionary sense in the ocean.

- The pinnipeds live mostly in marine environments; they spend almost all of their time in the water, but they come on land to mate and to birth their young.



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In the same way people form images with their eyes, dolphins form images of their watery surroundings using sonar.

- The difference between seals and sea lions is that seals have no external ear parts whatsoever—a more streamlined shape. They swim with a fused set of hind limbs that's essentially a single flipper and don't swim with their forelimbs at all. Conversely, sea lions have external ears. Their hind limbs are still partially separated, and their front flippers are also used for swimming actively.

- Walruses are the largest of the pinnipeds and the most massive. They live mostly in very cold-water environments where their massive size is an advantage to maintaining body heat.

- The largest of the seals and the most interesting is the elephant seals because they spend a lot of time on land.

- Sea otters are the geologically most recent newcomers to the ocean, and they're the only marine fissipeds. They can be found in the kelp forests of California, in large numbers in the Pacific Northwest, as well as in many other places around the Pacific.

Marine Mammals: Cetacea

- Cetacea include whales, dolphins, and porpoises. They are the large organisms that spend their entire life cycle at sea and don't come out for giving birth to live young. They evolved from early ungulates, so their closest land relatives are sheep and horses.

- The order of Cetacea can be broken down into 2 categories: Odontoceti, the toothed whales, and Mysticeti, the baleen whales.

- The toothed whales are the top predators of many fish and invertebrates in the ocean. They exist, for the most part, at a very high trophic level. The dolphins, porpoises, orca, beluga, and narwhal are all examples of toothed whales.

- Odontocetes have small to moderate sizes relative to mysticetes. The sperm whale is the largest of the toothed whales. They're all extremely skillful, fast-moving predators.

- All odontocetes share echolocation. They use very sophisticated combinations of clicks in the form of rising and falling tones—a sophisticated sonar. We suspect that dolphins and whales are very intelligent organisms.

- There's evidence that the sonar is not just used to locate prey, but it is used to stun their prey with extremely loud bursts of sound energy up to 230 decibels. Their large, convoluted brains may be used to process these audio tools.

- Baleen whales, mysticetes, don't have teeth. Instead, they have a horn-like, fibrous material that hangs down inside their mouth called **baleen**. As a result, they feed mainly at the surface, taking in great amounts of water that can be strained for small organisms.

- The baleen whales use sound as well. In fact, they are famous for their whale song. They emit low-frequency but loud sounds that can be heard over long distances—perhaps thousands of miles across the open ocean.

Important Terms

baleen: Horn-like fibrous plates used by Mysticeti whales to strain plankton from seawater.

Cetacea: Taxonomic group of marine mammals descended from land ungulates that includes dolphins, porpoises, and whales.

fissipeds: Marine mammal group including sea otters; in the same order as dogs, cats, bears, and weasels.

pinnipeds: Marine mammal group including seals, sea lions, and walruses; in the same order as dogs, cats, bears, and weasels.

Sirenia: Taxonomic group of marine mammals that includes manatees and dugongs.

tubenose: Taxonomic group of far-traveling marine birds including albatrosses, shearwaters, and petrels.

Suggested Reading

Berta, Sumich, and Kovacs, *Marine Mammals*.

Schreiber and Burger, *Biology of Marine Birds*.

Questions to Consider

1. Do any birds live exclusively at sea?

2. Most marine mammals are quite large organisms; there are no tiny ones similar to mice, for example. Why might it be difficult for a small marine mammal to exist?

Whaling, Fisheries, and Farming the Ocean

Lecture 22

Ocean fisheries are a major source of food and a highly efficient industry, but most species are being overfished to unsustainable levels, necessitating fish farming, or aquaculture. Whaling, now so controversial, was the foundation of much of the U.S. and European economy in the 19th century. In the past 15 years, there has been a more than 60% increase in the total catch from the ocean. Aquaculture is an increasingly important part of the overall fish supply—with its own impacts on the ocean environment.

The Whaling Industry

- Whaling, now controversial, was the foundation of much of the U.S. and European economy in the 19th century. People have hunted whales for thousands of years. Indigenous people of the Pacific, in particular, were adept at catching whales for food and for all of the different potential products they could derive from whales over long periods of time.

- Inuit hunters to this day in the northern regions of Canada are still engaging in traditional whaling and, by international convention, are allowed to take a certain number of even large whales that are otherwise protected.

- The whaling industry took off in the late 1700s and early 1800s and then again in 1868 with the invention of the harpoon gun. A few decades later, the beginnings of mechanized ships instead of sailing ships caused the rate at which whales were being taken to rise exponentially.

- By the 1930s, whale stocks were down to tiny percentages of their original numbers. Blue whales were down to 4% of their original stocks—almost extinct—and the same was true for many other large marine mammals.

- The International Whaling Commission (IWC) was founded in the mid-1940s to try to manage the whale population through international treaty. In the 1980s, the IWC banned all large whale hunting. Basically all the countries of the world stopped whaling—except for traditional uses and for Japanese so-called research whaling for minke whale.

- Today, most species are commercially extinct and not recovering quickly. Some are endangered and some are threatened, but species such as fin, gray, bowhead, humpback, and blue whales are at best recovering very slowly even though they're not being fished.

- There are a lot of whales in the ocean, but most of them are minke whales—a particular species that represents 700,000 or more of the probable population numbers today.

- Because the minke whales were relatively abundant and not seen as threatened or endangered, Norway and Iceland decided to resume harvest of these whales in the 1990s. Japan was already doing it and continued to raise their number of harvested minke whales. This is also being done for sperm whales and Bryde's whales.

- Today, there's a present catch of minke whales in the hundreds per year, which is believed by most marine-mammal experts to be sustainable. In other words, there are enough numbers of them out there—and they reproduce fast enough—that the rate at which they are being harvested does not really pose a threat to the minke whale populations.



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In recent years, the population of bluefin tuna has been rapidly declining due to the increase in popularity of sushi.

Ocean Fisheries

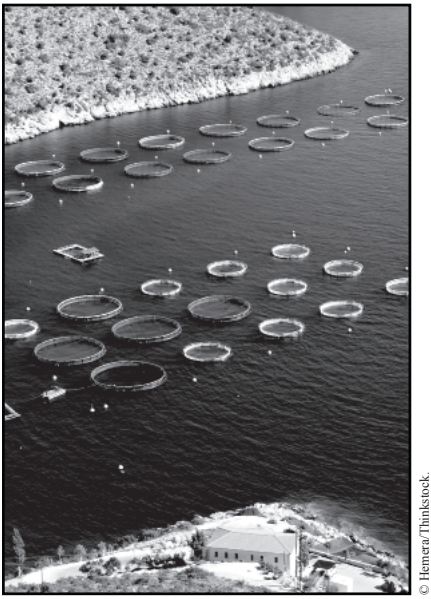
- Ocean fisheries are a major source of food and a highly efficient industry. The most interesting thing about ocean fisheries is that of all the things human beings eat on this planet and commercially expend energy to produce and sell as food, it's the only significant source of wild-captured animal food.

- About 79% of all fish from the ocean is wild capture, and 21% of the fish from the ocean is **mariculture**, or fish farming of the ocean. By contrast, the land-based freshwater aquaculture—the growing of fish for food in freshwater using freshwater species—is a rapidly growing industry that has become 46% of the total supply.

- Globally, fish are being caught at phenomenal rates, and they're largely not reproducing fast enough for the wild fisheries to keep up.

- Data from around 1992 shows that the commodity fish—white fish such as cod, hake, and haddock—represented a fairly large proportion, greater than about 10–15% of the total catch of wild fish. Tuna, bonito, and billfish were about 4% of the total catch. All the various fish represented about 87 million metric tons of weight in that particular year.

- Today, the total wild-capture fisheries have largely plateaued and not grown in size much since the late 1980s and early 1990s. Less than 8 million metric tons of the commodity fish—cod, hake, haddock—are being caught today. By contrast, the catch rate of tuna and bonito are going up rapidly, as are mollusks such as squids.



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Fish farming involves using the ocean as a medium to grow fish for human consumption in contained areas.

- Both scarcity and fashion shape these trends: For example, the global explosion of the popularity of sushi has changed tuna fishing greatly. This trend, however, appears to be on a collision course with a rapid decline as these populations are overfished as well.

- Quite simply, human population growth is driving all of this growth in the fishing industry. The number of people on the planet is continuing to increase at an exponential rate. There are twice as many people on Earth today as in 1965, and fish is a high-quality food that is relatively inexpensive to produce in aquaculture, so it's taking up the slack.

Worldwide Fish Production

- For a long time, the North Atlantic Ocean was the biggest fishery, with the Pacific Ocean second to it. Today, the Northwest Pacific Ocean accounts for 20% of the fishing industry, and the Pacific Ocean accounts for well over 50%.

- This is partly the historical trend of fishing having been developed in different parts of the world earlier versus later. In addition, this trend is due to the great growth of the Chinese fishing industry as well as other countries—including the United States—intensively fishing the Northwest Pacific and Bering Sea.

- The Atlantic Ocean catch is declining rapidly after peaks in the early 2000s. The Pacific Ocean trends have been growing rapidly over the years but are now leveling off, and catches are not increasing despite an increase in effort by increasingly technological fishing fleets. The Indian Ocean catch is sustaining, but patterns are changing—especially with a declining tuna catch.

Capture Fishing

- By far, the largest type of open-ocean capture fishing in tonnage is trawling for fish, which involves trawling with large nets. The mouth of the net is open, and the net mesh in size is configured to catch particular species or groups.

- There are fundamentally 2 types of trawling: mid-water trawling, which involves dragging a trawl net through the middle of the ocean, and bottom trawling, which involves a trawler with heavy weighted wheels that roll across the bottom of the ocean and scoop up everything in its path.

- **Bycatch** is a huge problem in the fishing industry because up to 25% of all the fish that are caught through trawling are non-targeted species. Basically, any type of fish that is a bycatch of what is being targeted is mixed in with the targeted fish but is dumped back into the ocean as a dead fish.

- A second major type of fishing that's used to target large open-ocean fish like tuna and swordfish is **pelagic longline fishing**, in which long filament lines are stretched out from ships that have floats along them to keep them in the near surface and individual baited hook lines that hang to catch fish. This type of fishing has relatively small amounts of bycatch, but unfortunately the bycatch tends to be organisms that are endangered.

- One type of open-ocean fishing that is essentially banned by international convention is drift-net fishing, which is similar to longline fishing by deploying very long nets that actually act like fences in the sea. Fish are caught by their gills as they try to swim through these nets, but the nets also catch anything that runs into them—including dolphins and seals. Drift-net fishing has been banned, but it is still practiced.

Fishery Management

- The **maximum sustainable y`ield** refers to how much of any fish species can be harvested each year in a given fishery region without depleting stocks for future years. There's a current estimate of all fish as food in the global ocean of between about 100 and 135 million tons per year, but that includes fish farming activities as well.

- The open-ocean fishery appears to be right at the maximum sustainable yield—or perhaps even on the high side—for the wild-capture fish that we're currently fishing economically in the ocean. Many of the specific species in the ocean are certainly overfished.

- An estimated 72% of all fisheries are being overfished today, and many of the others are right at their maximum sustainable yields. Overfishing beyond sustainable yields leads to a threat of the collapse of a fishery.

- The **tragedy of the commons** is the idea that if there's a resource like a wild fishery that's available to a large group of people in common, it benefits each individual member to maximize his or her use—even if it would be better for everyone to get together and agree to limit their own catch.

- The personal economics that fishing-boat owners face forces them, in the face of a declining fishery, to redouble their efforts. The replacement for most of this is aquaculture, which might ultimately take some of the pressure off open-ocean fish.

- The other form of fish farming that is becoming more common, but growing more slowly, is mariculture: the farming of marine seawater organisms such as shrimp and oysters. Mariculture is probably not going to replace the open-ocean fishing industry in the way that inland aquaculture is going to. What will make the most difference are environmentally responsible fish choices—both by business owners and by consumers.

Important Terms

bycatch: Non-targeted fish caught collaterally during commercial fishing; often discarded as noneconomic.

mariculture: Fish farming, or growing fish for food in ocean-water tanks or pens.

maximum sustainable yield: The amount of a given target species that can be caught each year without long-term depletion of the stock.

pelagic longline fishing: Fishing method employing baited hooks on a kilometers-long main fishing line, used for fish that have high trophic levels—such as swordfish and tuna.

tragedy of the commons: Concept articulated by Garrett Hardin that when a resource is available to a large group in common, it benefits each member to maximize his or her use—even if it would be better for everyone to limit their use. Applied to the problem of fishery management.

Suggested Reading

Greenberg, *Four Fish*.

Melville, *Moby Dick*.

Philbrick, *In the Heart of the Sea*.

Questions to Consider

1. A question to ponder, or discuss with others: Is (a) all whaling morally wrong; (b) acceptable as long as the species being hunted is harvested sustainably (i.e., not to the point of endangered or threatened status); or (c) all whaling acceptable as morally neutral economic activity? How does your answer differ for whales versus fish or versus the hunting of wild land mammals?

2. Should fish farming replace all wild-caught fish as production of commercial meat on land has become exclusively farmed, or could there be a place for wild-caught fish for the foreseeable future?

Where Sea Meets the Land and Why Coasts Vary

Lecture 23

The characteristics of coasts are governed by the interplay of erosional and depositional processes resulting from sea-level changes, plate tectonics, glacial cycles, and other factors. Erosion-dominated coasts exhibit rock cliffs and fjords—resulting from land uplift due to plate tectonics or glacial retreat—or drowned river valleys that result from rising sea level. Mechanical breakdown of rock to sediment by wave action is the major erosional process. Net accumulation and movement of sediment dominates on depositional coasts, producing long beaches, barrier islands, coastal plains, and wetlands.

Coastal Processes

- The characteristics of coasts are governed by a dynamic balance between 2 fundamental sets of processes: erosional processes and depositional processes resulting from sea-level changes, plate tectonics, sediment transport, and other factors.

- The shore, or the shoreline, is the physical place where the ocean meets the land—the location of interaction of the waves and the tides with the landscape. The coast, or coastal zone, more typically refers to the whole region of interaction of the 2—from some distance above high tide (perhaps marshes, sand dunes, and cliffs) to the immediate offshore sandbars and channels.

- The coast is an active place, subject to geological processes of both the land and the geological and oceanographic processes of the sea. It's a battleground between all of these forces and a dynamic balance, in fact, among all of them, which causes a place where basically nothing is static.

- The position of the shoreline is determined by factors that constantly change through time. The first one is tectonic activity (or the lack thereof), which can include motions due to plate tectonics and changes in the land level due to a process called glacial rebound—involving areas that have large glaciers on the surface, weighing down the land.

- An additional factor governing sea level is the movement and trapping of sediments, which involves the way sediments move around and build up in piles, dunes, sandbars, and reefs that potentially change the shoreline position.

- Perhaps most importantly, or most rapidly changing, is global sea level—also called eustatic sea level—which is defined as the variations in sea level that can be equally measured all over the world.

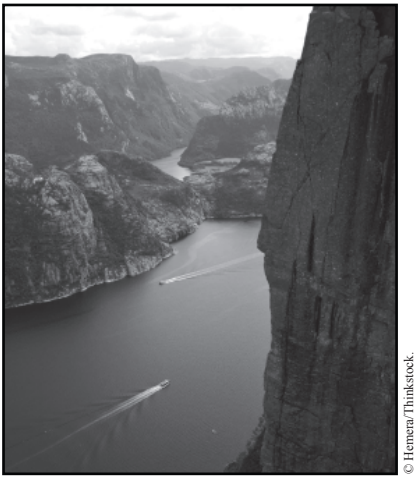
- Sea level has fluctuated on the geologic timeframe quite rapidly. The recent level is near the highest it has ever been—or at least over the past 250,000 years. Shorelines change in response to the rising and falling sea level, so shorelines change over time as a result.

- The long-term eustatic sea level is complicated because not only does the sea level rise relative to land, but the land doesn't stay in one place. Even the volume of the ocean can change; for example, more productive mid-ocean ridges raise the sea floor.

Erosional Coasts

- Erosional coasts are dominated by the breakdown of rock and the creation of sediment—the active modification of the rocky landscape of the planet. The mechanical force of the surf pounding on the coastal rocks, the hydraulic pressure driving water into the cracks in those rocks, the abrasion by the sand and gravel, and even boulders that water carries are the main agents of change for erosional coastlines.

- Since sea level goes up and down, the waves make **wave-cut platforms**—flat regions of bare rock that have been chopped out by the waves—in different regions, cutting the cliffs back and adding sediment to the sea, which ultimately moves around and forms beaches.



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In coastline areas of Norway, Alaska, and New Zealand, narrow inlets known as fjords often exist between cliffs.

- A typical erosional coast has some basic features. The sea cliffs have active wave-cut platforms at the base, and the sediment that's produced on those will start to fill in some areas with what are called exposed beaches, or pocket beaches. There are headlands of rock areas that are out beyond the beach that are sometimes eroded offshore as **sea stacks**, which are large rock promontories that jut out of the ocean but are no longer connected to the land—at least not at high-tide levels.

- In areas around the world's strongly erosional coasts, there are very active promontories of headlands of rock with cuspate pockets that will develop beaches in between them. When tectonic activity is strong and the land is actively being uplifted by the motion of faults, abandoned wave-cut platforms are developed.

- These cuspate bays are areas where waves are less strong, so sediment tends to fall out of the water. It deposits sediment in the bay—producing pocket beaches—while it focuses its energy and keeps the sediment in suspension, abrading and breaking down the rocks of the headlands. Given enough time, coasts that are craggy will slowly develop long, extended beaches from pocket beaches.

- Erosional coasts can also be shaped by land erosion. When the sea level was lower and the shoreline was out near the edge of the present-day continental shelf, rivers would cut river valleys down through the landscape. Ultimately, if sea level rises again, these regions become flooded by the influx of the sea, producing flooded river valleys.

- Perhaps the most dramatic example of that kind of erosional process is the development of **fjords** in places such as Norway, Alaska, and New Zealand, where there are dramatic glacially cut valleys from large glaciers that were present during the ice ages when the sea level was lower.

Depositional Coasts

- Depositional coasts are regions where the net accumulation and movement of sediment (sand and mud) shapes the fundamental morphology of the coastal area. The deposition of beaches, barrier islands, sandbars, and spits is associated with sand transport along a depositional coast.

- In the absence of ongoing tectonic activity and major sea-level changes, erosional coasts will gradually turn into depositional coasts. Long, sandy beaches are the result of the deposition of sand.

- In the near-shore region, where the waves break on the beach, the part of the beach that is actively washed back and forth by waves in typical weather and tides is called the foreshore. The foreshore is backed by what is called the backshore. The boundary between the foreshore and the backshore is the upper limit of the highest high-tide wave action—an area called the beach **berm**.

- There can be several beach berms on a given beach. Sometimes there's a higher beach berm that is the break and slope between the steeply sloping foreshore and the more gently sloping backshore. The highest beach berm might be produced by the largest recent major winter storm, and there can be a second beach berm that might be associated with the most recent tidal cycles or wave action.

- In the backshore region, instead of wave-dominated or water-dominated processes, sediment transport is taken over by wind-dominated and land-dominated processes to form such elements as sand dunes. There is often a very prominent break in the slope of the beach that defines that beach berm.

- Equally offshore, there is a region where sand and sometimes mud—finer-grained materials—are being actively transported back and forth by turbulent wave action right in the foreshore region, which builds a foreshore terrace on a flat spot.

- This flat spot often drops off into a longshore trough, which is a trough that runs along the length of the shoreline. The turbulent action of the water flowing back to the ocean digs out the sand a little bit and piles it up into a **longshore bar**.



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The Outer Banks region of North Carolina is dominated by extensive barrier islands created by longshore drift.

Longshore Drift and Current

- Sand moves up and down the beaches in very specific directions. **Longshore drift** is a very important process that continuously transports sand and sediment along the beach so that a dynamic balance of sand moves through that system.

- An offshore current called the longshore current is similar to the longshore drift—both involve the oblique approach of waves. For longshore current, the way waves break along the beach produces water moving in the near-shore offshore region laterally along the beach in the same direction as longshore drift, carving out the longshore trough and moving sediment laterally along the beach.

- Sediment transport by longshore drift and the presence of storms produce some very distinctive features that exist along the coastlines of the world such as barrier islands, lagoons, and sand spits.

- In some cases, the longshore bar can gradually turn into barrier islands—the long, extended islands that lie just off the main coastline that dominate many regions of depositional coast.

- As sand is drifting along the coast with the longshore drift, if it reaches an embayment—the mouth of a bay or river—then it reaches a point where the water gets a little deeper and the wave action is a little less strong, so a lot of the sediment will be dropped out of suspension and deposited as sand spits and sandbars that partially or completely cover those river mouths and harbor areas.

- Barrier islands are incredibly well developed around the eastern and Gulf coasts of the U.S. The North Carolina barrier islands (the Outer Banks region) and all the regions from the eastern shores of Maryland and Virginia down the coast are dominated by extensive barrier-island systems that are all offshore bars created by the longshore drift.

- Some of the features of typical east-coast barrier islands of the United States include the beach; the dune fields; and behind those, a broad and extremely low-elevation salt-marsh and tidal-flat region. Often these extend over many square miles into a saltwater lagoon or even brackish-water lagoon before reaching the mainland.

- One interesting feature of beaches with coarse sediments is that the beach tends to have a steeper slope to the ocean. On these slopes, water percolates into the coarse sand, so the beach develops a steeper face that has a very regularly spaced pattern of what are called beach cusps. The formation of beach cusps and their regular spacing is enigmatic; there are a number of theories about how they might've formed, but none offer a clear explanation.

U.S. Coastal Areas

- The Pacific coast of the continental United States and of Alaska is dominated by the fact that it's an active tectonic margin. It's a region where plates are converging, or moving past each other. The effects of recent tectonic activity render it dominated by erosion.

- By contrast, the Atlantic coast is a passive continental margin. Remember that the plate boundary is far out in the Mid-Atlantic Ridge, and there's no boundary between the ocean plate and the land plate. It's a depositional-dominated coastline—except for the flooded valleys that exist there.

- The Gulf coast, similarly, is a region that has smaller wave sizes; it's an enclosed basin. It's a passive continental margin, so it's also a depositional-dominated coastline.

Important Terms

berm: The prominent break in slope on many beaches that marks the highest elevation of wave washing.

fjord: Glacially formed deep and steep-walled valley flooded by the sea.

longshore bar: Sandbar parallel to the coast and just offshore in the tidal range.

longshore drift: Net transport of sediment parallel to the coast due to prevailing wave directions and variable swash and backwash on the beach.

sea stack: Rocky outcropping near the shore but isolated from the mainland created by erosional retreat of sea cliffs over time.

wave-cut platform: A near-flat bedrock plane cut by wave action eroding the coast between high- and low-tide levels.

Suggested Reading

Carson, *The Edge of the Sea*.

Pilkey, Neal, Kelley, and Cooper, *The World's Beaches*.

Sverdrup and Armbrust, *Introduction to the World's Oceans*, chap. 18.

Questions to Consider

1. Can a coastal area be both erosional and depositional at the same time?

2. Is a sandy beach on a deposition-dominated shoreline the same from season to season and year to year? What are some ways in which it is not the same?

Where Rivers Meet the Sea—Estuaries and Deltas

Lecture 24

Human activity is now extensively modifying the natural deposition and erosion processes on coastlines and, combined with gradual sea-level rise, is causing loss of beaches and natural barriers in many areas. Construction of breakwaters and jetties interferes with natural longshore drift and has caused wholesale changes in Atlantic coast shorelines. Seawalls and other structures designed to protect buildings ironically can make beach erosion worse. Loss of sediment supply and protective vegetation leaves many coastal areas more susceptible to storm damage. Private property rights, insurance, and public interest often collide over these issues.

Estuaries

- River mouths, deltas, tidal inlets, fjords, and enclosed bays are all regions where freshwater and seawater mix in a complex and dynamic environment of very high biological diversity and productivity. Many marine organisms have parts of their life cycle in these settings or even up freshwater rivers, including larval stages of **anadromous fish** like salmon as well as many crustaceans.

- **Estuaries** are bodies of shallow water that are partially surrounded by the land but with an open though limited connection to the ocean. Water in these areas is diluted to less than seawater salinity, but it is not as fresh as river water is.

- Estuaries are typically affected by the tidal range and are marked by exceptionally high biological productivity. Shallow, sunlit waters that have nutrients from both the land and the ocean mixing together produce a very fertile region on the planet.

- One example of an estuary region is the Chesapeake Bay and the flooded river mouths that enter it—such as the Susquehanna River. Another example is the San Francisco Bay, which is on the opposite coast but is also a shallow-water estuary.

Types of Estuaries

- The 4 types of estuaries are defined by their origin. Some are drowned river mouths, such as the Chesapeake Bay. In the continental United States, the Puget Sound region is a drowned fjord. Others are tectonic estuaries, which are formed by the action of faults and the upwarping and downwarping of the crust—San Francisco Bay is an example. The fourth type is the bar-built estuary that exists behind the barrier islands and sandbars where there are **lagoons** and salt-marsh regions—such as Pamlico Sound in North Carolina.

- Instead of the container—the estuarine basin—estuaries can be defined in terms of salt water and freshwater mixing.

- A salt wedge estuary is a region where there is very strong river flow into a confined basin that leads out to the ocean. This type of estuary is dominated by freshwater flow.

- Salt water is denser than freshwater, so the dense salt water is trying to move up the estuary with tidal cycles and wedges underneath the freshwater that's flowing over the top of it. There's a sharp boundary between the 2 water masses, and there's relatively little mixing. There's such a density difference between the cold, dense seawater and the river water that the river water flows on top of the seawater.

- One process that takes place in salt wedge estuaries is one-way mixing, an entrainment of salt water with some turbulence at the edge of the boundary up into the freshwater, which becomes more brackish as it heads toward the ocean. The salt wedge itself doesn't get much freshwater mixed into it.

- A second type of estuary is a well-mixed estuary, which has relatively low river flow and strong tidal mixing. The water coming in from the sea and the water coming in from the river are balanced. The waters mix actively and quickly, so there's a salinity gradient that doesn't have the depth stratification as in a salt wedge estuary but instead has nearly uniform depth.

- In between these end-member categories are partially mixed estuaries, regions where there is a strong flow of river water and also a relatively strong influx of seawater that produces even more turbulence and 2-way mixing—entrainment of some seawater up into the river water but transfer of some of the river water down into the seawater by turbulent vortex mixing at the boundary between the 2.

- The fourth type of estuary is a fjord-type estuary. Fjords commonly have deep water in them; they have what is almost a shallow-water barrier at the front end of the estuary, and the fjord is filled with a deep pool of fairly dense seawater. The river water enters the deep pool of salt water but remains at the surface and mixes very little. Many fjords have a very strong inversion in which the surface water is almost purely fresh but is completely saline water below a certain depth.

Well-Mixed Estuaries

- The Chesapeake Bay is an example of a well-mixed estuary. The salinity is measured in per mil—one part per thousand—and the peak salinity near the entrance of the estuary is in the 24–25 per mil range, and then it goes up to mostly freshwater at the upper reaches of the Chesapeake Bay. (The salinity of seawater is about 35 per mil.)

- The pattern of salinity is not particularly symmetrical in the Chesapeake Bay. As the salt water enters with the tides and, conversely, as the freshwater comes down from the rivers, the Coriolis effect causes the salt water to bend to the right (east) as it enters the Chesapeake Bay and the freshwater coming down toward the ocean to also bend to the right (west).

- The mixing of freshwater and sea-water nutrients in this shallow, well-lit, protected environment provides a fertile habitat for animal life that's specific to the estuarine waters. In particular, crabs, oysters, and many different types of fish dwell in estuarine environments and provide great fisheries and food sources for the ecosystem and for human beings.

- In addition, estuaries serve as nurseries for the juvenile stages of many major oceanic species. Examples include perch, anchovy, and Pacific herring.

- The Chesapeake Bay is home to the famous blue crabs, which have a fascinating life cycle. They mainly live in the low-salinity areas, relatively high up the estuary. A female mates only once in its life and carries the male sperm, but she needs to create and fertilize eggs—spawning the larval stage—which depends on getting to a high-salinity region and having lots of tidal water cycling.



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The famous blue crabs of the Chesapeake Bay region are a very tasty product of this estuarine environment.

- In high-estuarine environments that are well up into the upper reaches of the intertidal zone, where water reaches and creates brackish but also very slack water conditions, there are regions that are coastal salt marshes. In coastal salt marshes, there are salt-tolerant species—those that have evolved the ability to excrete salt—of many vascular plants and many aquatic organisms that thrive in that same environment.

Types of Deltas

- River deltas form where rivers with heavy sediment load reach the sea, especially in a region where the continental shelf is relatively broad and there's relatively low-energy wave action to carry that sediment away once it's been brought down to the sea.

- The combined effects of waves, tides, river flow, and sediment determine the 2 fundamental delta shapes: river-dominated deltas and tide-dominated deltas.

- **River-dominated deltas** are fed by a strong flow of sediment from the land with large distributary channels—regions where the river dumps its sediment load in one area for awhile and, as that builds up, moves off to a different region and dumps its sediment there.

- **Tide-dominated deltas** are molded by tidal currents that rework or move around the sediments that are being dumped by the rivers on the land.

- Both river-dominated deltas and tide-dominated deltas can be sites of major wetlands and salt-marsh regions, estuarine systems that can be extensively developed along the coastline.

- The Mississippi River delta, a river-dominated delta, builds out into the Gulf of Mexico at the coast of Louisiana and dumps sediment out over a large area. There, huge coastal wetlands—mud flats essentially—are interacting with the tides on a daily basis and are flooded by seawater, but they are also affected by the freshwater coming from the land.

- A river-dominated delta has the characteristics found at the Mississippi delta where the distribution of salt marshes and the channels are well defined by the fact that the river is putting sediment in the water out toward the sea.



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The Mississippi River delta, off the coast of Louisiana, produces hundreds of thousands of acres of coastal wetlands.

- By contrast, the Ganges River delta is a tide-dominated region, so the river is still coming down to the ocean and is still delivering a lot of sediment to the ocean, but it's delivering a little less sediment—spreading it over a broader and flatter region—and the tidal cycling is strong enough that it's taking all that sediment and redistributing it.

Biologically Dominated Coastlines

- Mangrove trees are rooted down into the salt water of a saltwater-dominated estuarine system but have leaves that are up in the air; they are partly marine and partly subaerial. Mangrove regions trap sediment, hold it in place, and build the land in tide-dominated regions.

- Coastlines can be dominated not just by erosion and sediment transport, but also by the biology that lives on them. Mangrove trees represent a whole type of coastline.

- At the fundamental geological level, coastlines start out as deposition dominated or erosion dominated, but the shore region and environments of the shoreline can often be substantially modified by the existence of ecosystems of various kinds of organisms.

- Mangrove trees can build huge areas of biologically dominated coastline by trapping large amounts of sediment and providing habitat for various organisms that then colonize the estuarine environment and use it productively.

- Mangrove forests essentially armor the coastline, making it less susceptible to storm surges and extremely high tides because they provide a buffer zone between the coastline and the main part of the land.

- Unfortunately, mangrove as wood is a potential commodity, and the mangrove regions are being taken over for various kinds of development. Globally, there's been about a 20% reduction in the total area of mangrove forests since 1980, but that rate is rapidly diminishing.

- Another type of biologically dominated coastline is carbonated banks and platforms. Coral reefs build large structures of carbonate; the reef itself is the living carbonate. The reef is constantly broken down, producing huge volumes of carbonate sediment—essentially limestone—over geological time. This process builds up a rocky substructure that's incredibly strong and becomes the main coastline feature.

- Many of the coral islands around the world were corals that grew up to close to sea level when the sea level was substantially higher than it is today. As the sea level drained back down, these corals dried out and died but left behind islands. The Florida Keys and the Bahamas are examples of such islands.

- Estuaries, deltas, and marine wetlands are among the most biologically productive regions on Earth and have in fact supported the flourishing of major world civilizations throughout human history.

Important Terms

anadromous fish: Fish that spend part of their life cycle in freshwater and part in the ocean, such as salmon.

estuary: Coastal body of water where seawater and stream- or river-supplied freshwater mix.

lagoon: Shallow saltwater region trapped between the beach dune zone and the mainland area.

river-dominated delta: A river mouth in which the strong flow from land determines the pattern of sediment deposition and channel geometry.

tide-dominated delta: A river mouth in which the waves and tides determine the pattern of sediment deposition and channel geometry.

Suggested Reading

Davis and FitzGerald, *Beaches and Coasts*.

Questions to Consider

1. What are some of the ways that pollution in estuarine waters are especially harmful to ecological communities relative to in the open ocean? See how many different aspects you can think of.

2. What might you expect to happen to present-day river deltas if sea level continues to rise?

Coastal Erosion—Beaches and Sea Cliffs

Lecture 25

Human activity is extensively modifying the natural deposition and erosion processes on coastlines, and combined with gradual sea-level rise, is causing loss of beaches and natural barriers. Construction of breakwaters and jetties interferes with natural longshore drift and has caused wholesale changes in shorelines along the Atlantic Coast. Seawalls and other structures designed to protect buildings ironically can make beach erosion worse. Loss of sediment supply and protective vegetation leaves many coastal areas more susceptible to storm damage. Private property rights, insurance, and public interest often collide over these issues.

Coastal Erosion

- Sea level has been rising slowly for many decades as a consequence of long-term natural climate change and is accelerating in recent decades due to global warming—affecting estuarine habitat, beaches, barrier islands, and wetlands alike.

- Sea level rose rapidly as Earth came out of its last ice age about 18,000 years ago; over several thousand years, it rose at a rate of about 2 millimeters per year. Several thousand years ago—between 2500 and 4000 years ago—sea level stabilized, slowing down to a few tenths of a millimeter per year.

- The present-day rate of sea-level change is about 3 millimeters per year, which is significantly faster than the rate at which sea level changed as Earth came out of that glacial period. This current rate is also accelerating.

- As sea level rises, communities want to protect coastal real estate and preserve beaches, which are a main source of recreation and income for coastal communities. Coastal communities use various methodologies and engineering to achieve these goals. Engineered structures vary in their efficacies: Some work well, but others do not.

- Many of these engineered structures are extensively modifying the natural deposition and erosion processes on the coastlines, causing the loss of beaches and natural barriers in many areas.

Sea Level

- **Eustatic sea level** is the global change of sea level, which is averaged over the whole planet. There's an interplay of eustatic change with local changes in land elevation due to tectonic activity and land subsidence.

- Tectonic activity refers to the uplift of the land through fault action or glacial rebound in many areas on the west coast. Especially in the Gulf Coast and Mississippi delta region, subsidence can occur due to the compaction of the soft sediments that lay beneath the ground, resulting in the extraction of water from trapped pore spaces.

Changing Sea Level around the U.S. Coastline

Sandy Hook, New Jersey: 3.90 mm/yr since 1933, about 1 foot total.

Galveston, Texas: 6.39 mm/yr since 1908, or about 2 feet total—due to the process of land compaction.

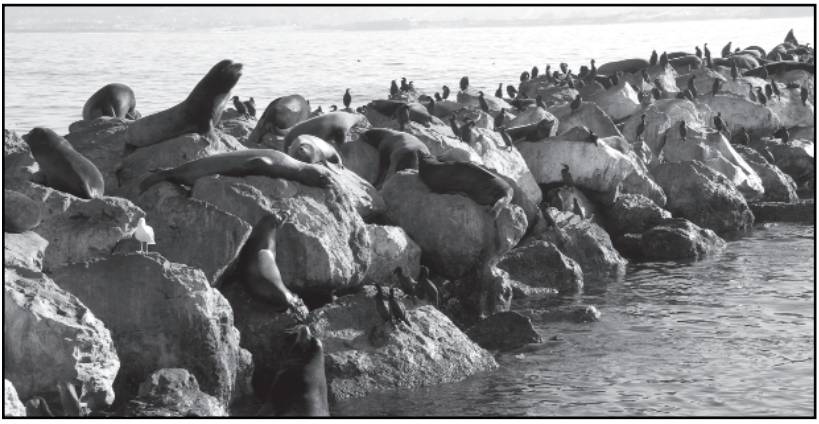
Seward, Alaska: –1.74 mm/yr—due to tectonic activity (huge jump in sea level in 1964 due to earthquake).

- In most places, sea level is rising at a rate of several millimeters per year—and from 3 to 6 millimeters or more per year around most of the North American coastline. If present trends continue, sea level will rise even more over the course of the next century.

- One of the effects of local sea-level rise is that it causes problems at the coast; storm surges, large waves, and the highest of the tides cause flooding at increasingly higher levels in many coastal communities, especially along the U.S. east coast.

- Storm surges and the erosion of beaches result when large waves invade coastal areas. The erosion-deposition balance is upended or modified by the higher sea level and stronger wave action. Barrier islands migrate toward the mainland, causing more beach loss.

- In addition, local sea-level rise causes the balance in estuaries and wetlands to change. If sea level is higher, estuaries and wetlands are flooded by seawater to an increasingly greater extent. The salinity zones also tend to migrate inland, changing the habitats for various organisms. Habitats change and can't always migrate along with the changing salinity zones and changing mixing zones in the estuaries.



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Jetties are built in coastal areas to protect the harbor entrance and to stop longshore drift.

Responses to an Eroding Shoreline

- We human beings like to respond to an eroding shoreline in different ways, but mostly what we tend to want to do is stabilize the shoreline.

- One response is referred to as **hard stabilization**: the construction of seawalls, breakwaters, groins, and jetties—engineered structures whose purpose is to stop the sand from moving around too much.

- Another response is called soft stabilization, which involves beach replenishment or nourishment.

- A third response is to move, relocate, or retreat from the shoreline as shorelines erode and sea level rises.

Hard Stabilization

- In terms of hard stabilization, there are a number of different protective structures that can be helpful. First, jetties are rock structures—essentially walls—that are built perpendicular to the shoreline to protect harbor inlets by temporarily blocking or deflecting longshore drift.

- Building jetties, however, prevents the longshore drift from continuing to deliver sand to the down-shore side, which needs that sand to replace the longshore drift that it in turn is handing off to the next part of the beach.

- A groin is like a jetty. It's a smaller type of seawall that is built perpendicularly and in periodic distances along beaches to prevent the loss of sand from longshore drift that is occurring along the beach.

- Groins and jetties interfere with longshore drift and have caused major changes in some shorelines on the Atlantic coast over the course of recent decades. Preventing the sand to move is actually preventing the natural process that replenishes the beaches over the course of the entire Eastern Seaboard.

- **Breakwaters** are structures that are built parallel to the shore and in shallow water off shore to provide an area protected from the waves. The process involved with blocking wave input causes wholesale changes in the ocean—or in the coastline—given enough time.

- Another type of structure that's designed on the coastline to protect buildings and keep the beach or sea cliffs from eroding are called seawalls. Seawalls are any kind of hard structure that's meant to armor the coastline and make it more resistant to the eroding power of the waves. Ironically, seawalls can actually make beach erosion worse at times.



© Andy Coburn, Western Carolina University
Program for the Study of Developed Shorelines.

Beach replenishment is necessary when communities lose their beaches to beach erosion.

- Southern and Northern California are places where expensive beachfront real estate is being protected by very large-scale, massive engineering projects—called hard-barrier construction. In these areas, concrete and very large boulders are piled up at the base of a cliff to try to prevent the waves from breaking on the bottom of the cliff. If waves continuously undercut the cliff, the cliff eventually slumps down and becomes sediment.

- Typically, hard-barrier constructions are eventually battered against by the waves enough that they become undercut. When the wave energy hits a seawall instead of dissipating on an open sandy beach, it undercuts the seawall region, causes greater offshore erosion, and eventually undercuts it so much that the seawall collapses.

- Seawalls can also be built right on a beach, as opposed to in a sea-cliff region, to provide a hard barrier so that manmade objects like houses and hotels can be built very close to the shore. If this is done in the right part of the beach—well into the backshore region above the highest of the potential berms—then it can be a reasonable structure.

- Unfortunately, because people want to maximize their beachfront real estate, they build seawalls a little too far out. If the seawall is built out into the active berm region or into the foreshore region, then the waves will wash up to it at high water and in storm surges and will reflect off the seawall and undercut it, exacerbating beach erosion as opposed to preventing it.

Soft Stabilization

- **Soft stabilization**, beach nourishment or replenishment, is another process that's become much more popular in recent decades. Soft stabilization involves importing sand to the beach to replace sand that has disappeared through the active erosional processes associated with either sea-level rise or longshore drift.

- Beach nourishment can take the form of dredging up sand from longshore bars off shore and placing it back onto the beach or mining sand from somewhere else. Both practices involve building up the amount of material on the beach.

- Beach replenishment has been done in many places, especially along the Eastern Seaboard in the United States. It's a popular activity with local beachfront communities because as they lose their beaches to beach erosion, they lose their livelihood.

- Many tens of millions of dollars have gone into beachfront replenishment of limited areas of the shoreline in well-developed communities. It works very well for a time but depends on the local region and significant storm events. Beach replenishment is not going to stop sea-level rise; it's just a way of adding more material for the sea to move along in longshore drift.

- In the estuarine regions of the planet, such as marshlands and mangrove forests, the loss of sediment supply or the loss of the mangroves is leaving many coastal areas more susceptible to storm damage and to loss of land area because of rising sea level.

Sea Level and Society

- Private property rights, insurance, government, and public interest often collide over issues of coastal erosion. The fundamental problem is not so much that the sea level is rising as the fact that the coastline is, in its natural state, a dynamic environment where the landscape is shifting at all times.

- Beaches will continue to exist whether the barrier islands migrate landward or whether sea level drops and barrier islands migrate seaward. What causes the problems is the act of trying to fix them in place and denying the fact that they are dynamic structures on a geological basis.

- Sand beaches and barrier islands are all naturally in dynamic equilibrium with longshore drift. As sea level rises, they're going to inexorably change and migrate landward. Eventually, engineering will not be able to stop it because sea level will continue to rise.

- The government funds beach-nourishment projects for recreational beaches at expenses of up to hundreds of millions of dollars, and it's only a short-term solution. Society can direct that the money be spent for the public good of having recreational beaches in place.

- In addition, there are long-term solutions that do not involve moving people back from the beach or reconstructing the same areas after storms but that instead involve making provisions for retreat from what is surely a retreating shoreline.

Important Terms

breakwater: A rocky barrier constructed parallel to shore and just off shore to protect from wave action.

eustatic sea level: The globally averaged elevation of the sea surface.

hard stabilization: Construction of a solid barrier such as a seawall to lessen or delay the effects of beach or sea-cliff erosion.

soft stabilization: Addition of sand to a beach through beach replenishment or nourishment to mitigate beach erosion.

Suggested Reading

Garrison, *Essentials of Oceanography*, chap. 11.

Pilkey, Neal, Kelley, and Cooper, *The World's Beaches*, chaps. 4–8 and 12–13.

Pilkey and Young, *The Rising Sea*.

Pugh, *Changing Sea Levels*.

Questions to Consider

1. We've seen that sea level has always risen and fallen in cycles over time immemorial. What's the problem with sea-level rise now?

2. What is likely to happen to most barrier islands as sea level rises? What about coral reefs?

Tidal Life, Sea Forests, and Coral Reefs

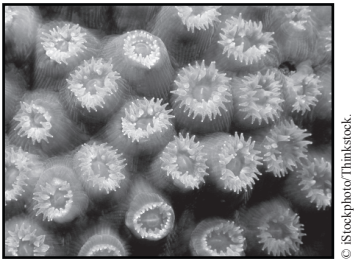
Lecture 26

The ocean floor hosts the most complex and varied ecosystems in the sea, which vary based on such factors as the type of substrate, access to light, and wave energy. The intertidal zone includes seaweeds and mangroves and the many organisms that live around them. Sandy and rocky beaches are relative deserts, dominated by burrowing organisms. Coral reefs and atolls are built up in the photic zone by colonies of coral polyps. The reef structure hosts a teeming community of organisms in complex predator-prey relationships.

Benthic Communities

- The ocean floor, from the rocky intertidal zone of the beaches out to the edges of the continental shelves, hosts the most complex and varied ecosystems to go along with all the locations that life can inhabit in the sea.

- These ecosystems vary—from coral reefs to kelp forests to open mudflats—based on the kind of substrate, the access to light, and the wave energy in the ocean. These regions are the benthic, tidal, and subtidal zones within the sea.



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The reef structure itself is composed of limestone that is secreted by the coral polyps.

- Benthic communities are ecosystems of organisms that are located on or near the bottom of the sea. The habitat for these benthic communities range from rocky tide pools to coral reefs, sandy beaches, abyssal deep vents, and open sea floor.

Marine Ecosystems

- A community is a group of different types of organisms that inhabit a particular location or environment. By contrast, a population is a group of organisms of the same species occupying a specific area. Communities are made up of a variety of populations.

- A habitat is the specific environment in which any given organism or any given population lives. The ecological term niche refers to the specific role a particular organism plays in the community. An organism has an ecological niche, which is distinct from its physical habitat.

- Sandy and rocky beaches are relative biological deserts. There aren't vast numbers of organisms, and they aren't very productive in terms of overall biomass productivity. In fact, they're dominated by burrowing organisms.

- The reason that sandy beaches are relative deserts is because a sandy beach is an inhospitable environment. Sand is a loose, sharp, and abrasive substrate. High wave energy and shifting sand make it difficult for an organism to stay in one place. It's also difficult for an organism to keep from getting eaten if it is constantly being washed out of its habitat and into another zone.

- On the other hand, beaches are constantly washed over by waves, so even though they're relatively poor substrate regions, there is a lot of organic matter that infiltrates into the pore spaces in the sand. Every wave carries with it some organic material and plankton, providing food for burrowing organisms that can take advantage of it—such as crabs, clams, polychaete worms, and sand fleas.

- The intertidal environment includes mangrove forests as well as rocky tide-pool habitats. The major challenges for organisms living in a rocky coastline environment are coping with constant wave action and tides.

- The organisms that live in rocky tide pools have developed several strategies for coping with the high-energy, rapidly changing environment. The payoff for these organisms is that waves continuously bring in nutrients from the sea and from the land.

- A typical tide pool involves numerous different individual organisms and populations of organisms in a complex community in which they're all dependent on the different parts of the ecological process that the other ones are carrying out. A typical tide pool includes fish, mussels, crawlers (snails, chitons, and limpets), algae (seaweed), starfish, hermit crabs, gulls, and sea urchins.

- Change is a very important aspect of tide pools. As a result, many of the organisms that live in a tide pool—even the ones that are sessile like a sea anemone—have developed the ability to handle periodic drying. Organisms that can handle this kind of environment are the ones that are good at remaining in place, which is important.

- Sea anemones are cnidarians, so they are filter feeders: They open up their polyps and waft water or filter feed detritus and plankton into their mouths. When the tide pool dries out, as it periodically does, the anemones are efficient at having a harder exterior that allows them to close up to maintain the water content and protect it from damage from the sunlight.

- In rocky tide pools, there's an incredible vertical zonation: Parts of this tidal ecosystem have very specific zones relative to low-tide and high-tide lines.

Seaweed and Kelp Forests

- For many areas, especially in rocky environments and the temperate zones of the world, below the intertidal region in the euphotic zone is dominated by seaweed and kelp forests of various kinds.

- Seaweed and kelp forests are enormously productive ecosystems that rival rainforests on land for the biomass production per square meter.

- The most famous are the California kelp forest or the kelp forests of the Pacific Northwest and Alaska. These zones are where the kelp fixes itself down to the bottom—which is why they are benthic organisms—and then grows up into the sunlight for vast distances.

- Kelp are seaweeds, not plants, in terms of biological kingdoms. Kelp are protistans, a form of multicellular algae. Seaweed can range from microscopic to hundreds of feet in size. Seaweeds are autotrophs, and they photosynthesize within the euphotic zone.

- There are 3 types of seaweed: green (Chlorophyta), brown (Phaeophyta), and red (Rhodophyta) algae. All types of seaweeds have different adaptations to different environments within the ocean.



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Ecosystems that are dominated by kelp forests and seaweed rival rainforests for biomass production per square meter.

- Giant kelp are the type of seaweed known as brown algae and can grow 50 centimeters per day to over 40 meters long. They dominate the kelp forests found on the west coast of North America. Giant kelp act as **holdfast** anchors to rocks on the ocean floor and grow up to the surface of the water. They also exude carbohydrates into the water.

- Kelp communities dominate especially rocky coastlines all over the world. Mangrove communities dominate many of the regions that kelp don't. Many of the tropical to subtropical regions that aren't sandy beaches or depositional coastlines are dominated by mangroves. The temperate regions and the high latitudes are dominated by kelp forests—a significant proportion of the total coastline of the world.

Coral Reefs

- Besides the mangrove and kelp forests that are so productive, the other offshore environment is the coral reefs and atolls, which are built up in the photic zone by colonies of coral **polyps**—animals that host photosynthesizing single-celled algae within their bodies. Corals are another incredibly complex environment where there are interactions among a number of different organisms to keep the entire reef healthy.

- A coral is an animal—not some kind of plant. A coral is a cnidarians related to the anemones and jellyfish. Coral polyps wave in water to entice fish and zooplankton and then sting them with their nematocysts and pull them in for digestion.

- Most corals are colonies of individual polyps. Each polyp is actually a separate animal. A coral head is a colony of many thousands of those individual animals. Most corals build up reefs, and this type of coral is called **hermatypic coral**.

- The success of corals depends critically on a symbiotic relationship. Coral polyps trap floating plankton and even small fish. At the same time, they host specialized microscopic dinoflagellates called **zooxanthellae**, which are the photosynthesizers. This is a very efficient exchange between primary producer and consumer.

- The coral creates the habitat to maximize the benefit for the zooxanthellae, which creates very strict habitat needs for the corals. First, corals need bright light; they have an optimal zone between about 5 and 10 meters deep in the water. They also need normal to slightly high salinity to keep the coral polyps in a good osmotic situation, and they need temperatures above 21°C.

- The reef structure, the limestone that's secreted by the coral polyps, is strong to withstand high-energy wave action. The coral reef is always breaking down and getting busted up by waves—almost as fast as it builds.

- The reef has nooks and crannies everywhere. It hosts many different coral varieties that are competing constantly with each other and a teeming community of other organisms in all sorts of complex predator-prey relationships.

- Corals are under increasing environmental pressure. One of the things that is an incredible challenge but is unclear why it happens is a phenomenon called coral bleaching, in which healthy corals suddenly turn into essentially completely white corals and ultimately become covered by algae.

- Coral bleaching results from a small rise in temperature in the water—for reasons that are unclear. Even a 1°C or 1.5°C change in water temperature can cause the corals to spontaneously expel all the zooxanthellae that are in their polyps. The coral turns white because of the loss of the pigmented photosynthetic algae. The polyps can continue to live for awhile based on their normal consumption of food, but if this continues for too long, the coral dies.

- Coral bleaching is a big problem all over the world. In areas such as the U.S. Virgin Islands, about 60% of the corals that were formerly healthy have now succumbed to coral bleaching. With the changing global water temperature and, more importantly, the changing acidity of the water, corals may not be able to continue to build reefs in the future.

- Other than zooxanthellae, there are other types of corals on the planet, including many that are called **ahermatypic corals**—corals that are soft and don't build reefs. Many of these don't have to live where the light is filtering down through the water. There are deepwater soft corals in regions that are much colder—off the coast of northern Europe, for example. These are much less common and much less abundant than the hermatypic corals of the classic coral reefs.

Important Terms

ahermatypic coral: Soft coral that makes no hard reef structures.

hermatypic coral: Coral that secretes carbonate and builds up reefs.

holdfast: The anchor of a kelp seaweed that fixes it to the substrate, as roots do for vascular plants.

polyps: The individual coral animals, similar to sea anemones, that collectively make up the colony in a coral head.

zooxanthellae: Microscopic dinoflagellate photosynthesizers that live symbiotically and are hosted by coral polyps.

Suggested Reading

Cousteau, *The Silent World*.

Questions to Consider

1. Benthic communities have much more diverse populations of species than open-water pelagic communities, but benthic communities are also more geographically limited in area. Why might this be so?

2. Corals themselves are only a small number of the diverse species that make up a coral-reef ecosystem. What factors might contribute to making reefs so diverse?

Deep Bottom Life and Hydrothermal Vents

Lecture 27

The deep-sea floor is vast and populated by scavenger communities. The most fascinating of all deep benthic communities are those of the deep-sea vents, where key symbiotic relationships feed ecosystems that may be the key to the origin of life on Earth. Hydrothermal vents at the mid-ocean ridges fuel an entire ecosystem based not on sunlight but on chemosynthesis. Unique symbiotic relationships between bacteria that chemosynthesize and larger fauna such as tubeworms, crabs, and clams are the basis of these strange vent communities.

The Deepest Zones of the Sea

- In the mid 1800s, Edward Forbes began dredging up samples from along the continental shelf and into the beginnings of deep water. He found life in these samples, but they were dwindling in number with depth.

- He extrapolated to a depth of about 500 or 600 meters and said that this was the **azoic zone**—a region in the bottom of the sea that would have absolutely no life because it was deep and dark.

- However, nothing could be further from the truth. Today, we know that the deep sea is populated to the greatest depths of the ocean.

- In the late 19th century, the *Challenger* expedition found that there was a jellylike mass—some sort of protoplasm—that covered the entire ocean floor and that it was one single living organism, which was given the name *Bathybius haeckilii*.

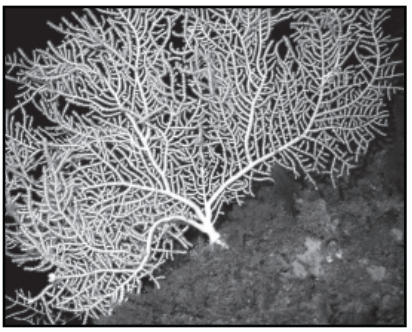
- *Bathybius haeckilii* was simply a mistake. It was an interesting sidetrack on the way to understanding that the deep-sea bottom has a whole variety of many different species and is a zone of oases and differences.

Down the Continental Slopes

- The abundance of life, the biomass, does diminish rapidly as you move off the lit continental shelves and into the deep water. Even down the continental slopes, a number of **sessile** organisms—those rooted into the sea bottom—live on the ocean floor.

- The mud that blankets the continental slopes from terrigenous sedimentation is processed and digested by a range of both **epifauna** (live on the ocean floor) and **infauna** (live burrowing within the ocean floor). Macrofauna—fish, skates, and cephalopods in the form of octopuses and squids—live near and adjacent to the ocean floor and graze on these organisms as well.

- For example, some of the epifauna and the sessile organisms that root into the sea floor include sea fans, or gorgonians, that are common in the coral reefs, but they're also present all the way down the continental slope and into even deep water. Sea pens are another example.



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Gorgonians are common in the coral reefs, but they're also present down the continental slope and into deep water.

- Both sea fans and sea pens are cnidarians. They're essentially polyps, and they're filter feeders. They're related to corals and sea anemones.

- Deepwater anemones are also present in these depth zones, and they all share the trait of sticking up into the water so they can filter the slow-moving water currents.

- Deepwater corals form masses that are called bioherms, or accumulations of biological material that build up on the ocean floor. These corals do not have zooxanthellae; they don't photosynthesize. Instead, they live as polyps and as primary consumers.

- All deepwater corals are living on detrital material. In fact, at the bottom of the ocean, it's continuously snowing—called **marine snow**, which is the constant raining of dead parts of organisms that live far above in the shallow waters.

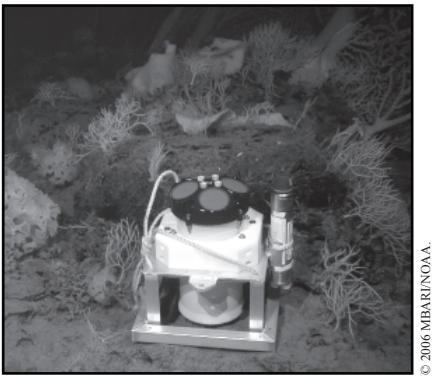
- There are many macrofauna associated with the continental slopes as well. For example, a giant isopod is truly daunting in size and can move remarkably quickly. It's basically a scavenger that is a carnivore of fish and even squid.

- On continental slopes, there is a great profusion of crabs. Skates and rays are also present. Octopus are tremendously common on the continental slopes and out on the deep-sea floor as well as rattail fish, which hover just above the sea floor and feed on the epifauna and infauna they can find there.

- There are entire sets of habitats associated with small rocky outcroppings on the continental slope and on the abyssal plains, including out on the seamounts that stick up from the deep-sea floor into shallower but still deep water.

- In many places, seamounts are rocky outcroppings that stick up from the 4000-meter ocean floor up to 2000 meters or 1000 meters in depth. Ocean currents sweep over the tops of seamounts.

- Filter feeders are especially abundant on top of seamounts. In the waters of the lower continental slope and out on the broad abyssal plains, one of the most common kinds of organisms is ophiuroids, which are commonly known as brittle stars. They are echinoderms (meaning having spiny skin) and are similar to starfish, but they're especially well adapted to life in the deep sea. They can move quite quickly and can remain sessile without eating anything for weeks.



© 2006 MBARI/NOAA.

Researchers use current meters that are placed on the ocean floor to determine how currents affect various ecosystems.

- All over the world, brittle stars are virtually ubiquitous in waters below 500 meters of depth on the slopes and out onto the abyssal plains.

Abyssal Benthic Communities

- Broad abyssal plains represent the whole sea bottom. Through the first half of the 20th century, the abyssal plains were seen as monotonous zones where the same few life-forms probably dominated.

- Starting from the 1960s, when scientists became more sophisticated about how they sampled benthic fauna, it was discovered that there are surprisingly diverse life forms and robust ecosystems—even if the total biomass is relatively small on the deep-sea floor.

- Scientists from Woods Hole Oceanographic Institution devised a special sampling trawl called the epibenthic sled. They found hundreds of species and tens of thousands of individual organisms in each area of the epibenthic sled in an average place on the abyssal plain.

- Later, another study found 4500 organisms representing 798 different species in a single square meter of a typical abyssal plain. Overall, abyssal plains have a vast diversity of life existing in very specific niches that have evolved to work together and exploit every available resource in this relatively scarce zone of the deep-sea floor.

- Most of the surface of Earth is composed of abyssal plains, zones that are dominated by worms and echinoderms. Worms called polychaete, or bristle worms, are some of the best-adapted organisms on the entire planet.

- An acorn worm forms a U-shaped tube in the ocean floor and basically eats its way through the sediment.

- The kings of the deep-sea floor are the **holothurians**, which are echinoderms called sea cucumbers.

- A sea urchin tends to be circular with a pentagonal symmetry (a 5-pointed body plan), a central mouth, and an anus to expel food waste.

- All of these species that are similar to starfish and sea urchins are echinoderms, which are the dominant species in terms of processing the ocean floor.

- The real kings of the ocean floor, at least in terms of photograph ability, are the holothurians, the sea cucumbers. They're the real waste processors of the deep. They are completely soft and are inflated by water. When they want to move, they pump water into a particular pseudopod, or leg, and inflate it to move it—kind of like a hydraulic system.

- Sea cucumbers sometimes turn up in great profusion—by the thousands—in herds of sea pigs, or herds of holothurians, and are one of the most abundant organisms on the ocean floor.

- Every part of the ocean floor has moved through the gut of some organism multiple times over. Tiny differences in the available resources on the ocean floor have led to the evolution of different species in a patchwork all over the planet.

- Whale carcasses and presumably other large organisms that die in the water column somewhere and fall to the bottom are a great source of food.

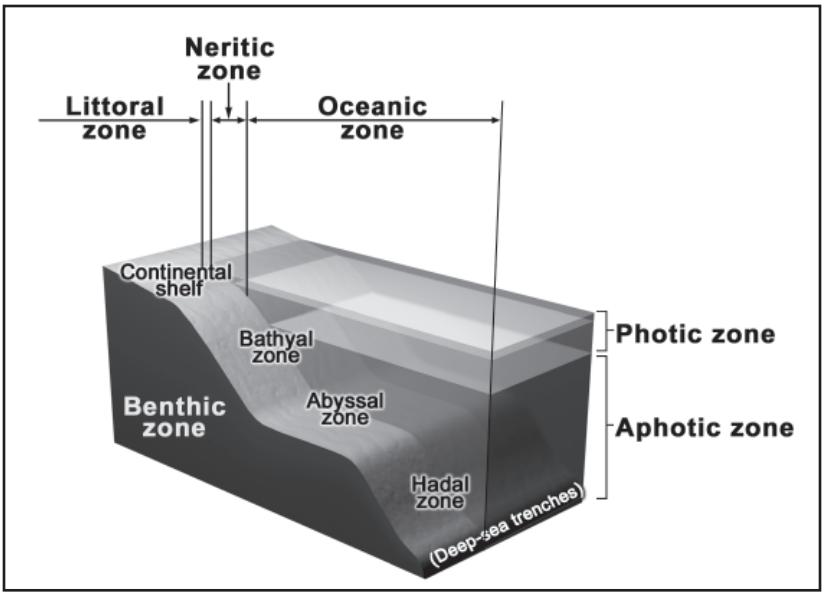
- Hagfish, specialized worms, sea cucumbers, and crabs all come in great numbers somehow smelling or sensing dead whales and digest all the available flesh right down to and including the bones—which is why we don't find as many fossils as expected in deep-sea sediments.

Deep-Sea Vent Communities

- There are vast profusions of organisms living around black smokers and hot hydrothermal vents in deep-sea vent communities. All the marine ecosystems we've discussed so far, including the detrital ones, are ultimately based on photosynthesis fueled by the Sun.

- Until the late 1970s, it was believed by all biologists that all life on Earth was based on photosynthesis. In 1977, the accidental discovery of a thriving benthic community—the deep-sea tubeworms and clams that were living at the hydrothermal vents of the East Pacific Rise—showed that an entirely different way of life exists.

- Chemosynthesis is a different pathway than photosynthesis that uses chemical energy, not sunlight, to make the carbohydrates and sugars that life depends on for food.



- If there is carbon dioxide, oxygen, and hydrogen sulfide in an environment, then an organism that can exploit this can use the energy in the hydrogen sulfide to make glucose. These organisms have had to develop an ability to resist the toxicity of sulfur to manage it and get it out of their bodies.

- Hydrogen sulfide comes out of the hot vent water of black smokers. There are bacteria that can oxidize the sulfide to make carbohydrates. These bacteria live freely in the water within some of the mid-ocean ridge vent rocks adjacent to the hottest water but also within the guts of the larger organisms that are around them in great profusions. There's a symbiotic relationship going on between them.

- In the gut of a very large tubeworm called rift tubeworms are great masses of these bacteria, which chemosynthesize. The bacteria make the food, and the worm lives on the food—the only food it receives.

- Very large clams, mussels, and crabs live in deep-sea vent communities and feed off the food generated by the clams, mussels, and tubeworms—the **chemoautotrophs**—which all share one really interesting trait: Their flesh is red. They have this red flesh because they bear hemoglobin, which they need to bind the sulfur and get it out of their systems. Their red flesh stinks of hydrogen sulfide.

- Shrimp living in this environment have special organs on the backs of their heads and can sense the heat from the hot vents coming out of the water. They orient themselves around these hot vents. Based on a totally symbiotic relationship with the chemosynthetic bacteria, these communities evolved early and have been present at the bottom of the ocean for at least hundreds of millions of years.

- More than 900 species associated with hot vents have been catalogued. Organisms that can live in these hot-vent areas are sometimes called hyperthermophiles because they love heat. The hyperthermophiles can live in water in excess of 100°C.

- Chemosynthetic communities of other types have been located in environments that do not have hydrothermal vents. Some of the best-known ones are the communities of cold seeps, in which methane or hydrogen sulfide seeps out of the ocean floor. No special heat is involved, but the chemical energy is present.

- These cold-seep communities are comprised also of clams and tubeworms and some similar organisms. As oil and gas seep on the ocean floor, there are profusions of life because there's more energy coming out in places where those hydrocarbons are leaking out of the ocean floor.

Important Terms

azoic zone: Edward Forbes's briefly popular theory of the mid-1800s that no life existed below depths of about 900 meters; the theory was soon disproven by trawls and dredges.

chemoautotroph: Organism that manufactures food (carbohydrates) from the energy of chemical bonds.

epifauna: Benthic organisms that dwell on or above the sea floor.

holothurian: The sea cucumber or sea pig, a soft benthic echinoderm that scavenges the mud of the sea floor.

infauna: Benthic organisms that dwell within the sea floor.

marine snow: Clumps of whitish organic detritus that form a constant "snowfall" to the sea floor in deepwater environments; fuels scavenger ecosystems.

sessile: Animals unable to move about that are usually permanently fixed to their substrate, such as barnacles or corals.

Suggested Reading

Gage and Tyler, *Deep-Sea Biology*.

Van Dover, *The Ecology of Deep-Sea Hydrothermal Vents*.

Questions to Consider

1. One might think of the deep-sea floor as an unchanging habitat—a place with no seasons, cycles, or even events. In what senses is this true? Conversely, can you think of anything that could be seasonal or eventful there?

2. Why might chemosynthetic communities exist only in places like the deep-ocean floor rather than across a wide range of land and sea habitats, the way photosynthesis-based communities are?

Trade Winds—The Circulation of Heat and Wind

Lecture 28

The atmosphere and ocean are intimately linked in their motions, driven by the uneven distribution of heat modified by the Coriolis effect on all movement as Earth rotates on its axis. Uneven heating by the Sun from the equator to the poles causes density differences in air masses, which rise and fall accordingly, creating pressure differences that in turn drive the winds. Wind in general blows due to pressure differences in air; some wind patterns are persistent year after year. Mariners depended on knowledge of wind bands and calm regions for centuries of navigation.

Atmospheric Circulation

- Water is a fluid medium, and it's constantly in motion. Ocean currents cause the large-scale global transport of water that mixes the ocean over long timescales.

- The atmosphere and the ocean are intimately linked in how they move. The ocean wouldn't be in motion if it weren't for atmospheric motions and the wind blowing across the sea. The wind drives the surface currents of the ocean. It's a water planet, but that's partly because it has an atmosphere that moves around and transports heat on the surface.

- The air is approximately 78% nitrogen, 21% oxygen, 1% argon, and a small fraction of 1% carbon dioxide. The largest component after the nitrogen and oxygen is water vapor, which is primarily from evaporation off the surface of the sea.

- What moves the atmosphere around are differences in density that are set in motion by gravity and by differences in pressure. Density of the atmosphere decreases with altitude. Warm air is less dense than cold air, so density varies with temperature

- Humid air—air with more water vapor in it—is actually less dense than dry air because the molecule H_2O is lighter than the nitrogen or oxygen gas that makes up the rest of the air. Warm air can hold more water vapor than cold air can.

- The pressure of the atmosphere is 15 pounds per square inch at sea level, or what we call one atmosphere. That pressure is due to the weight of the entire column of air from sea level up to the top of the atmosphere.

- The pressure decreases as altitude increases. Higher up in the atmosphere, the air expands because the pressure becomes lower, and the expansion causes it to cool off. Conversely, it contracts and also warms when pressure is increased, so the higher the pressure, the warmer the air gets.

- When warm, humid air forms at the surface—just above the sea and the tropical regions—it starts to rise up to the upper atmosphere because of its lower density. The air expands, cools, and then is able to hold less water vapor in gaseous form and tends to form droplets. Therefore, clouds and rainfall are ultimately results of this atmospheric portion of the hydrological cycle.

- Uneven heating from the Sun warms the equatorial regions much more than it warms the polar regions. We think of the tropics as warm and the poles as cool, but this uneven heating drives the circulation of the air in the atmosphere.

- The equatorial region is hotter than the polar region because of the direct heating of the Sun versus the very oblique heating of the Sun in the polar regions or in the far latitudes north and south.

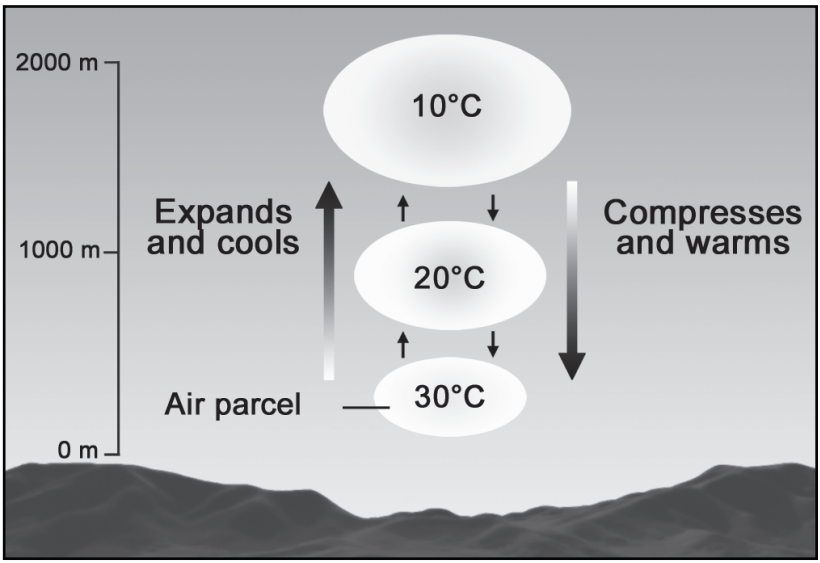
- The uneven heating of Earth—the imbalance of that heating on the surface of the planet—creates a surplus of heat tropically and a lack of heat in the polar regions, and the air starts to move in order to redistribute that heat.

- If there wasn't any movement in the atmosphere, the poles would be much colder and the equatorial regions would be much hotter than they actually are on our planet today.

- There's an uneven heating seasonally that warms the Northern Hemisphere and Southern Hemisphere at different times of the year. Seasons don't exist because Earth gets closer to and farther away from the Sun; they occur because of the angle that Earth makes with the direction to the Sun.

The Coriolis Effect

- We can think of a hypothetical atmospheric circulation on Earth due to uneven solar heating. There would be a giant convection cell in each hemisphere, much like convection in a pot of boiling water. These giant hypothetical convection cells on Earth don't actually exist because there's one more really important complicating factor: the **Coriolis effect**.



- The Coriolis effect was first described by French physicist Gustave-Gaspard Coriolis in 1835 and states that everything on Earth that's in motion is fundamentally affected by the fact that Earth is always rotating eastward. The Coriolis effect deflects objects.

- It takes 24 hours to complete one full turn on Earth. A place that's far to the north is rotating through a much smaller circle and with a smaller velocity than a place on the equator. Therefore, we're moving at different speeds depending on where we are on the planet.

- Moving objects in the Northern Hemisphere always look like they're veering to the right due to the Coriolis effect. In the Southern Hemisphere, the effect is the same but opposite: Everything looks like it's deflecting to the left.

- Interestingly, the Coriolis effect is zero at the equator. In general, the Coriolis effect is relatively weak when you're near the equatorial regions. This concept is important for understanding the flow of air and water. The Coriolis effect is strongest near the poles due to the rapid change in the amount of rotational velocity.

- The air in motion in the atmosphere is affected by the Coriolis effect as well. It moves poleward, but it's deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. It doesn't make it all the way to the poles.

Atmospheric Circulation Cells

- The atmosphere is broken down into, or develops, a number of different circulation cells. They're driven by convection, but they're not as simple as without the Coriolis effect. We can break down circulation on the planet into some very large, well-developed cells.

- From the equator to about 30° north latitude and 30° south latitude are the symmetrical Hadley cells. From 30° to 60° north are the Ferrel cells, and then above 60° all the way to 90° north or 90° south are the polar cells. These cells govern the generalized airflow pattern for the planet in 30-degree divisions with 3 parts in each hemisphere and 6 sets of cells overall. The Hadley cells, the Ferrel cells, and the polar cells are called **atmospheric circulation cells**.

- The subtropical trade winds, the temperate westerlies, and the polar easterlies are all the low-altitude arms of these major atmospheric cells.

Earth's Wind

- The wind blows because of pressure differences. Air simply flows from zones of high pressure to zones of low pressure. The rising warm and humid air creates a low pressure; the sinking cold and dry air creates a high pressure.

- **Trade winds** are driven by the fact that air rises and sinks. For example, the sinking cold air that's moving eastward comes back toward the rising warm, tropical air that's moving westward.

- Doldrums are regions of calm air where nothing much is happening. These are the places where the warm, humid air is ascending.

- In the boundary between the Hadley and Ferrel cells are the horse latitudes, where the cool, dry air descends. On land, this produces very persistent high-pressure zones that tend to be very dry.

- The big deserts of the world virtually all lie in this 30° to 35° belt north or south. The Sahara and the Gobi deserts are examples, and they are some of the driest places on Earth.

- The zones of intertropical conversions and the horse latitudes are zones where the wind doesn't blow very strongly. The winds in between are the important governing winds that move ocean currents around and also have moved mariners around the sea for a very long time.

- Trade winds come from the east and are called easterlies; in fact, they actually come from the northeast to the southwest. They are the surface winds of the Hadley cells and are centered around 15° north and south latitude. The westerlies, by contrast, are the surface winds of the Ferrel cells and are centered around 45° north and south latitude.

- In the polar regions, up at 70° or more north and south, there are the polar easterlies as well. The geometry becomes very simple: The boundaries are at 30°, 60°, and 90°, and then those strong winds are centered at 15°, 45°, and 75°.

- These wind patterns are persistent on average year after year, which is how the trade winds and the westerlies have gotten the name prevailing winds.

- In the days of sailing ships, mariners depended very specifically on knowledge of these wind bands in the calm regions. This type of knowledge was important not only for getting around, but also as part of their navigational strategy for understanding where they were north and south and moving across the oceans, when they were dependent on winds at all times.

- Columbus, the discoverer of America, actually never set foot in North America. He and his crew headed south along the African coast until they reached the latitude of about 15°, where they got into the trade-wind belt. They rode the trade winds westward across the Atlantic Ocean in order to travel west. When they got to the far side at that latitude, what they hit was not Florida and not the east coast of the United States, but the coast of the island of Hispaniola and other islands in the Caribbean.

Important Terms

atmospheric circulation cells: Large-scale, closed loops of overall mean airflow distributed according to latitude.

Coriolis effect: The tendency of any object in motion on Earth to deviate from a straight-line course due to the rotation of the planet.

trade winds: Prevailing easterly winds centered on 15° latitude north and south.

Suggested Reading

Aguado and Burt, *Understanding Weather and Climate*.

Walker, *An Ocean of Air*.

Questions to Consider

1. What do you think the Coriolis effect is like exactly along the equator?

2. Do prevailing-wind systems such as the trade winds still exert control on human activity and culture as they did in the days of sailing ships, or is that a thing of the past?

Heavy Weather—Storms and Hurricanes

Lecture 29

Differences in pressure between air masses and differences in heat energy between ocean and atmosphere cause major storms. Extratropical cyclones form at the boundary between Ferrel and polar cells. Tropical cyclones form within one air mass, fueled by the storage and release of latent heat by evaporation and condensation. Hurricanes build in intensity over warm ocean water, dissipate over cooler water and land, and move in predictable ways. The destructive power of hurricanes is in the force of the wind, the intensity of rainfall, and the storm surge that raises local sea level in front of the storm.

Major Atmospheric Storms

- Between the ocean and the atmosphere exist the air masses that drive the major atmospheric storms—from large-scale pressure cells that create gales to various kinds of extratropical cyclones and ultimately even hurricanes and typhoons.

- The sea breezes and land breezes at the coast exist due to a differential amount of temperature change of the land and the ocean during the day when they're both being heated by the Sun equally because of the different thermal capacity and thermal inertia of water versus the land.

- During enormous monsoon seasons of the Himalayas in India and the entire South Asian region, up to 425 inches of rain can fall over areas of India during the summer months.

- **Monsoons** develop for similar reasons as daily sea breezes. The ocean off shore in this subtropical region is relatively warm and very moist. It carries a lot of water vapor. It's being pulled in and then rising up the mountain front, where it's expanding because



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Torrential rains that form as a result of the monsoon season cause major flooding during the summer months in India.

of the decrease in pressure as elevation increases and dumping torrential rainfall. It's the changing pressure over the land sucking air in, and all the water that goes with it, off of the ocean.

- Conversely, the pattern reverses in the wintertime. Dry winters occur as dry air sinks off the Himalayan mountains and the Tibetan plateau—the exact same process of differential thermal inertia between the water and the landscape.

Storm Systems

- Storms are disturbances in large-scale flow patterns. Virtually all of the major storms, both winter and summertime storms, that we see in our parts of the world are cyclones, which are rotating masses of low-pressure air.

- All storm systems—hurricanes, northeasters, wintertime gales—have the same characteristics.

- Cyclones can form between 2 different air masses or at the boundaries between different air masses that have very different characteristics. They are bodies of air—with somewhat fuzzy boundaries—that have relatively uniform properties.

- Density drives pressure and therefore drives wind and air flow. Density is a function of the temperature of the air and the humidity in the air. Air masses get either relatively low density or relatively high density and form areas of relatively high pressure or relatively low pressure. Once they acquire these properties, air masses can maintain them for a number of days or weeks.

- The boundaries between the air masses are what meteorologists call fronts, which are areas of a large gradient in density and, therefore, a large gradient or change in pressure. When a front comes through, the wind blows very strongly because the air is rapidly changing in pressure—from low to high or high to low—in a particular region.

Extratropical Cyclones

- **Extratropical cyclones** are the famous winter storms called northeasters; extratropical cyclones form at the boundaries between 2 of the different major atmospheric circulation cells.

- An example of an extratropical cyclone is the record-setting weather that occurred in April of 2007 that affected the entire New England region as well as Canada and regions in Europe.

- Another example of a famous northeaster or extratropical cyclone is the one that became documented by the book *The Perfect Storm*: a 1990 storm that was a convergence of more than one extratropical-style cyclone in the northern Atlantic Ocean.

- In the Ferrel cell, the predominant wind patterns are westerly, which come across the North American continent and move toward the east. The colder air of the polar cell moves predominately from east to west.

- There's a strong front that commonly develops between the westerlies and easterlies at what's called the polar front. In a low region of air pressure, winds will tend to converge in that low. The westerlies will converge toward the low from the south, and the easterlies will converge toward the low from the north, rotating or twisting up the polar front.

- Cyclone storms can dump a lot of water, which is damaging in the form of heavy rainfall or snowfall in a region, but oceanographically speaking, one of the biggest effects is the development of a storm surge.

- As the wind blows across the water, it moves the water. If the wind moves in one direction long enough and strong enough, it will create a pile or hill of water in front of the storm.

Tropical Cyclones

- **Tropical cyclones** begin in tropical regions, and when they become strong enough, they attain the names hurricanes or typhoons.

- Tropical cyclones form within one air mass—not at the boundary between 2—and they're fueled by the tremendous amount of evaporation that's possible in a warm, tropical ocean.

- Tropical cyclones are essentially giant heat engines: They are individual masses of humid, warm, rotating air. They form initially as tropical depressions or low-pressure zones in the trade winds, and they form within one air mass over the ocean between 10° and 25° latitude—either north or south of the equator.

- In order to become full-blown tropical cyclones, these masses have to move over water at a temperature that's greater than about 26°C, which is quite warm water in the ocean.

- As tropical depressions form, they form a little bit of low pressure. Once the low pressure forms, then they can turn into tropical storms and ultimately cyclones.

- Tropical storms occur if the wind speeds are less than about 120 kilometers per hour, but they become hurricanes if the wind speed exceeds 120 kilometers per hour. A hurricane is what we call it in the Atlantic Ocean, but the same type of storm is called a typhoon in the Pacific Ocean.

- Hurricanes have a low-pressure core, and the wind comes in from all directions to try to fill in that low-pressure core. Hurricanes build in intensity over warm ocean water because evaporation continues to keep the pressure at the center low. If hurricanes move over cooler water or land, they will tend to dissipate because they lose that heat field.

- Tropical cyclones form in the tropical Atlantic Ocean—in the middle of the ocean between Africa and the Caribbean region. Tropical cyclones also form in the tropical Pacific Ocean—in the eastern Pacific near Baja, California, and in the western Pacific near the Philippines and Indonesia. Tropical cyclones form in the Southern Hemisphere as well, although they don't form to the same profusion as in the Northern Hemisphere.

- Once they form, tropical cyclones are masses of air that swirl in the Northern Hemisphere in a clockwise manner. As they move with the trade winds, they move in a western direction but will start to turn to the right—just as everything does—due to the Coriolis effect. Tropical cyclones always track westward and in the Northern Hemisphere, turn northward, and bend around.

- In the Northern Hemisphere, tropical cyclones rotate counterclockwise; in the Southern Hemisphere, they rotate clockwise because of the opposite Coriolis forces in that region.

Hurricanes

- The center of a hurricane is the region where an ultralow pressure develops and where water is evaporated off the surface of the ocean very quickly because it's so hot. As this moisture is picked up, it spirals up out of the air mass and exits at the top, dropping massive amounts of water vapor as it reaches the higher altitude levels of the atmosphere.

- The absolute center of the hurricane is called the eye of the hurricane, which is where the weather can actually be calm and clear.

- Hurricanes can have a structure of up to 1000 kilometers in diameter and 15 kilometers tall. The rainbands are rapidly spiraling clouds, copious rain of up to several inches an hour that move with the trade winds east to west.

- The year of Hurricane Katrina, 2005, was the world-record hurricane season for the Atlantic Ocean. This is because the heat generated by an incredibly strong high-temperature zone just happened to be present in the Gulf of Mexico at that particular time of the year in that particular year.

- Hurricane intensity is categorized by using the Saffir-Simpson hurricane scale, which categorizes hurricanes as a 1 through 5, depending on wind strength. A category 1 hurricane has to have winds that travel at speeds higher than 155 miles per hour, and a category 3 has to fall between 111 and 130 miles per hour, for example.

- The destructive power of hurricanes lies in the force of the wind and the intensity of the rainfall. More than anything else, the destructive power of hurricanes is experienced in the storm surge that raises the local sea level in front of the storm.



© USGS.

During Hurricane Ike in 2008, the barrier islands along the region around Galveston, Texas, had tremendous damage from storm surges.

- In the case of Hurricane Katrina, the city of New Orleans, Louisiana, was inundated by flooding as levees failed—not from the direct rainfall of the hurricane, but from the oceanic storm surge that pushed the water in and overwhelmed the city's levee defenses.

- The biggest tsunami are probably more destructive and bigger features than the largest hurricanes. However, hurricanes are somewhat more frequent.

- A storm surge, and the high waves associated with it, drives barrier-island migration over time. A huge amount of sediment transport occurs in the biggest storm events such as hurricanes and typhoons.

- Galveston, Texas, was hit by a hurricane in 1900 that was the worst natural disaster in U.S. history in terms of loss of life, even exceeding the losses that resulted from Hurricane Katrina.

- After 1900, a seawall was built called the Galveston seawall, one of the largest civil-engineering projects that had ever been undertaken at the time it was built. This seawall worked as designed during Hurricane Ike a full century later.

Important Terms

extratropical cyclone: Rotating mass of air formed by the disturbance of the boundary between polar and Ferrell cells; includes the northeasters.

monsoon: Seasonal weather pattern typified by heavy rain resulting from onshore flow of warm, humid air drawn in by rising air heated over mountain ranges in the summer, especially in the Indian subcontinent and Himalayan mountain front.

tropical cyclone: Rotating mass of tropical, low-pressure air with heavy winds and rainfall fueled by sea-surface heat; includes hurricanes and typhoons.

Suggested Reading

Emanuel, *Divine Wind*.

Sheets and Williams, *Hurricane Watch*.

Questions to Consider

1. A storm surge is sometimes called a storm tide. In what sense is it similar to and/or different from a tide?

2. Hurricanes and typhoons can be described as being heat engines. Where is the heat coming from and going to as a hurricane moves through an area of the ocean?

The Gulf Stream to Gyres—Vast Surface Currents

Lecture 30

The major ocean currents move vast quantities of water and are driven by the persistent westerly and trade winds of the atmospheric cells. The phenomenon of Ekman transport induces rotary current systems in each ocean basin called gyres. Western boundary currents (e.g., Gulf Stream and Kuroshio) are the deepest and largest; they move warm, tropical water poleward in both hemispheres. Eastern boundary currents (e.g., Canary and California) are wider and shallower and move cold water toward the equator. Gyre currents affect only the uppermost few hundred meters of the ocean.

Ocean Currents

- Ocean currents can be broken down into surface currents and much slower deepwater transport.

- The major currents—the Gulf Stream and its counterparts, for example—are surface currents of the ocean that are caused mainly by wind friction directly on the sea surface and by differences in the density of different water masses.

- Surface currents affect the uppermost 10% of the world's ocean. The shallow, warmer, lower-density waters are the places where the surface currents live.

- Surface currents are induced primarily by the prevailing winds. The westerlies and the trade winds are the most important ones for understanding the big currents on the surface of the ocean. The trade winds blow from the northeast toward the southwest, and the westerlies blow from the southwest toward the northeast. Both are in different latitudinal bands.

- The water moves with the trade winds, but it doesn't move in the direction the trade winds blow, and the same goes for the westerlies. This is because of the Coriolis effect.

- The water moves much slower than the wind. When water moves either north or south, Earth rotates beneath it and causes Coriolis bending. If the water moves slower than the wind, Earth is rotating more for a given unit of time and causes the water to bend much more than the wind.

Direction of Surface Water Flow

- If the wind blows in a given direction, the water is deflected and starts moving at about a 45° angle to the overall direction of the surface wind. The wind sets the surface water in motion, but it sets the water in motion at an angle to the overall wind direction. **Ekman transport** describes the phenomenon in which the surface water blows with the wind at a 45° angle.

- As we look deeper and deeper in the water over the upper hundred meters, each successive depth moves in a different direction that keeps changing in a characteristic way that produces what's called an Ekman spiral. The water itself is not actually spiraling, but the vector, or the direction, that shows the way the water is moving starts out at an angle to the wind that with successive depths moves in slightly different directions.

- The overall effect is that there's a spiraling direction of transport of the water such that at approximately 100 meters depth, the water moves much more slowly than at the surface, but it's moving in the opposite direction.

- For the surface waters down to about 100 meters, the net direction of the transport is perpendicular to the wind direction. This is what sets the surface-ocean currents in motion.

- As they move, they bend to the right very sharply, developing these loops called oceanic gyres—the major loops of the ocean circulation pattern of the surface currents that are persistent and very large scale.

- There is one major gyre for the North Atlantic Ocean, one major gyre for the South Atlantic Ocean, and a couple of major gyres in the Pacific Ocean.

- The current flow and the Coriolis effect combined in the form of an Ekman spiral drives all the water toward the center of the gyre, forming a dynamically balanced hill in the water.

- The fact that gyres are dynamically balanced means that water is piled up by the Coriolis forces of the currents, but it wants to flow back down because gravity wants to even the water out and maintain a constant water level. The competing effects of Ekman transport and gravity balance out.

- The oceanic gyres that are in this balanced flow system that causes the flow to move right around the gyre and stably maintain this dynamically balanced hill are called **geostrophic gyres**.

- The hill of water that sits in the Atlantic Ocean is called the Sargasso Sea, and it's a region where the water is relatively calm. This oceanic gyre in the North Atlantic has an elevation that is 2 meters high—higher than the average sea level for the Atlantic as a whole.

Major Geostrophic Gyres

- There are 5 major geostrophic gyres that are planetary-scale surface-current features: the North Atlantic gyre, the South Atlantic gyre, the North Pacific gyre, the South Pacific gyre, and the Indian Ocean gyre.

- The Antarctic Circumpolar Current is driven by the westerlies, hence the name it is also known as: West Wind Drift. It's the place that generates the biggest winds and the biggest storms on the planet because the wind blows continuously right around Antarctica.

- Within oceanic gyres, there are a number of types of major surface currents. The western boundary currents are the fastest and deepest currents on Earth. They move warm water from tropical regions to higher latitudes.

- The largest and most famous of the western boundary currents is the Gulf Stream, which moves at about 2 meters per second or as much as 5 miles per hour. It moves like a river that is out in the ocean.

- The Gulf Stream is about 70 kilometers wide and about 450 meters deep; it's a relatively deep trough extending down to the lowermost parts of the thermocline and pycnocline in that region. The Gulf Stream flows at a rate of 55 million cubic meters of water per second—55 times the flow of all the rivers in the entire planet.

- Eddies can spin off of the main western boundary current and persist for weeks at a time, even in the ocean, before they finally dissipate and remix. This is a major way in which the surface waters of the ocean get mixed across large areas of the sea surface.

Studying Currents

- Oceanographers study major surface currents of the ocean by using CTDs, which measure current velocity, temperature, and salinity with depth.

- Another way is to put special kinds of floating beacons or sensors out in the ocean that will drop down to a particular depth and take measurements.

- The most modern way to study surface currents is the use of robotic vehicles called AUVs, autonomous underwater vehicles. One example is called a Slocum glider.

- AUVs are special devices that are battery powered and use sensors to measure temperature and current speed. They can dive down to certain depths in the water, and they can change buoyancy and altitude in the water. Periodically, they are programmed to rise up to the surface and beam the information they're carrying to a satellite and the oceanographers on shore.

Western and Eastern Boundary Currents

- The second biggest and most famous example of the western boundary currents is the Kuroshio off the coast of Japan. The Kuroshio is important for tuna fishing and for all of the fisheries of the Japanese islands.

- There are also many eastern boundary currents in the world. Some examples include the Canary Current in the Atlantic Ocean and the California Current in the Pacific Ocean. They move mostly cold water toward the equator.

- Eastern boundary currents are shallow and very broad, and they're more diffused and move slower than western boundary currents. They might be as much as hundreds to thousands of kilometers wide but only a hundred meters in depth.

- The major eastern boundary currents of the world are the Canary Current in the North Atlantic Ocean, the Benguela Current of the South Atlantic, the California Current, the Peru Current in the South Pacific, and the current of Western Australia.

- The westward currents are intense, fast, and deep, and the eastern currents are spread out because of the Coriolis interaction with these geostrophic gyres.



© NOAA.

Mapped by Benjamin Franklin in the 1760s, the Gulf Stream is like a river out in the ocean.

Transverse Currents

- The boundary currents on the west and east are linked together by **transverse currents** that move water from east to west and west to east.

- In the middle latitudes, the westerlies drive the transverse flow—such as the Northern Pacific transverse current and the North Atlantic transverse current. In the Southern Ocean, the West Wind Drift dominates, so the far southern transverse currents are not very strongly developed. In the equatorial regions, the trade winds drive the north and south equatorial currents.

- The trade winds drive the equatorial currents because there's a meteorological equator on Earth that's different from the geographic equator. This has to do with the fact that there's a lot more land mass in the Northern Hemisphere and a lot more ocean area in the Southern Hemisphere.

- Oceanographers use many different kinds of information to learn about the ocean currents: drift cards, notes in bottles, and even serendipity.

- In 1990, a ship dumped several containers that contained 61,000 pairs of brand new Nike tennis shoes overboard in the middle of the Pacific Ocean. Some oceanographers found out about this and talked to the people involved with that ship to map out where the shoes had shown up—where they had been carried to by currents.

- In 1992, another spill put 29,000 bathtub toys into the Pacific Ocean, starting another flurry of activity to study how these toys could become oceanographic markers.

- All of these very important surface currents influence the climate of the entire planet because they're moving heat around on the planet. They're also influencing and making the large-scale mixing of the surface ocean water possible.

Important Terms

Ekman transport: The tendency of wind-driven surface currents to move at an oblique angle to the wind direction, caused by the Coriolis effect acting on the water. The effect increases with depth, creating the variation in motion direction known as the Ekman spiral.

geostrophic gyre: The hemisphere-scale surface-current loops set up in each ocean basin that are dynamically balanced by competing effects of Ekman transport and gravity.

transverse current: The generally east-west flowing surface currents that link the boundary currents and also account for the Antarctic Circumpolar Current (also known as the West Wind Drift).

Suggested Reading

Hohn, *Moby-Duck*.

Ulanski, *The Gulf Stream*.

Questions to Consider

1. Try to imagine the surface currents on a planet with no continents—only one big ocean. What form might they take? (Hint: Think of the Antarctic Circumpolar Current and extrapolate.)

2. Why don't the currents simply follow the prevailing wind cells?

Upwelling, Downwelling, and El Niño

Lecture 31

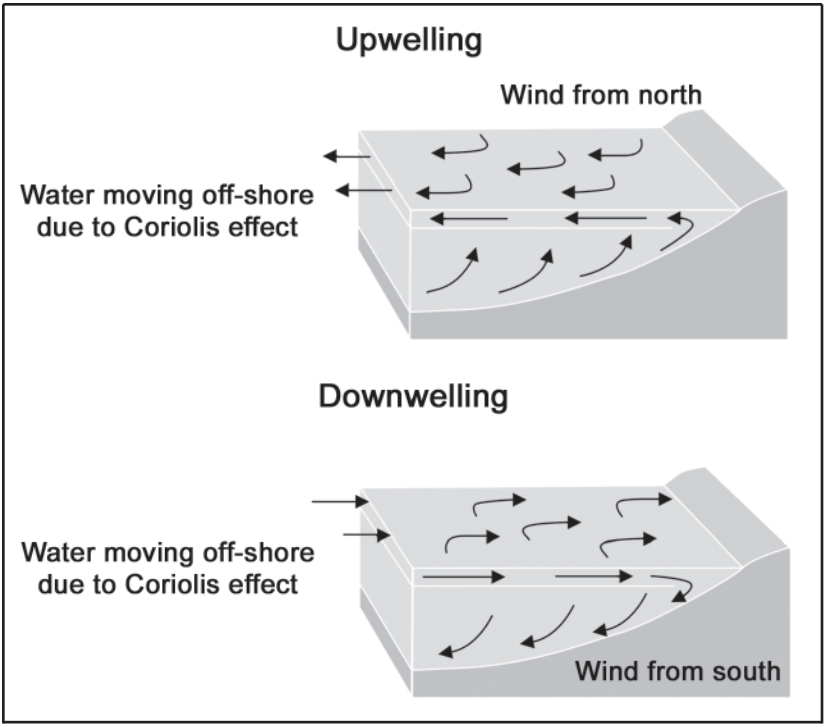
Vertical movement of near-surface waters driven by the wind, called upwelling and downwelling, is important in oceanic biological productivity and also plays a key role in the global climate phenomenon known as El Niño. Upwelling brings deeper, nutrient-rich water to the surface along the equator and many coastal areas, supporting major fisheries. Downwelling causes surface waters to sink, pushing the thermocline down, which reduces productivity. El Niño is a cyclical climatic effect in which the trade winds slacken, equatorial currents reverse, and downwelling replaces upwelling off the coast of Peru with climatic effects felt around the world.

Upwelling and Downwelling

- Vertical movement of near-surface waters, and even of waters significantly deeper than that, can be driven by the wind and by oceanic surface currents. These vertical movements are important in oceanic biological productivity and play a key role in the global climate phenomenon known as El Niño.

- **Upwelling** brings deep water, or water that's currently not at the surface, up to the surface. **Downwelling** causes surface waters to sink.

- Downwelling can have important coastal effects and is important for the formation of the deep water that fills up most of the ocean basins—called high-latitude cold-water formation.



- The south equatorial current moves water from east to west across both major ocean basins and flows essentially right along, or slightly diagonally across, the geographical equator. Meanwhile, the trade winds in the Northern Hemisphere and the Southern Hemisphere also blow east to west because they drive that current along the equator.

- In the Northern Hemisphere, the water turns away from the equator and toward more northerly waters. The water that's just a bit to the south of the equator turns to the left because it is in the Southern Hemisphere.

- The net effect is that the water at the surface is parting, and we call that process divergence. The south equatorial current parts the water, so deeper water wells up to fill in the gap. This parting of the surface waters pulls up colder water.

- The Coriolis effect causes the water to turn in opposite directions across the equator and, therefore, causes **equatorial divergence**, which in turn is the cause of equatorial upwelling.

- Most of the tropical regions of the euphotic zone are relatively barren of primary productivity because those warm surface waters are depleted in the key nutrients for photosynthetic activity.

- There's a very strongly developed thermocline in tropical regions—warm surface water, cold deep water, and a strong gradient between the 2. Surface waters are depleted in carbon dioxide because the photosynthesizers use it up.

- In deeper water, there exists the detrital food web, in which zooplankton and all the other consumers break down organic matter and re-release nutrients along with a lot of carbon dioxide.

- In deeper water, an upwelling takes place, the waters part, and deeper water wells up, bringing dissolved carbon dioxide–rich water and other nutrients to the surface, which facilitates great masses of phytoplankton blooming along the equatorial region.

Upwelling and Productivity

- Phytoplankton blooms can be seen from space. The SeaWiFS satellite measures ocean color, which is directly converted to a measure of the presence of chlorophyll for these phytoplankton. The phytoplankton feed a localized food web along the tropical region.

- Upwelling is induced by the combination of the equatorial current and the trade winds. Coastal upwelling is another process that is very important for biological productivity.

- In the California Current, for example, a combination of wind blowing and water flowing along the coastline causes Ekman transport to take place. Ekman transport actually means that as the wind blows along the coast, the water moves perpendicular to the coast and off shore.

- If there's a barrier in the form of a coastline, then the water moves away. There's no surface water to replace it, so it draws deep water up—in the same way as with equatorial water.

- In places such as California and Peru, coastal upwelling is a very important process that moves a large amount of water from great depths up to shallow areas. This deep water is drawn up from even thousands of meters deep in the water and replaces the surface water, producing a voluminous amount of nutrient-rich water that arrives at the surface and fuels major phytoplankton blooms.

- The phytoplankton in these areas are the basis of a highly productive food chain. The famous fisheries of California, Peru, and the areas in South America of anchovy and sardine—as well as fisheries in rich Antarctic waters that have the same kinds of coastal upwelling—are all fueled by upwelling productivity.

- The converse to upwelling is downwelling, which is the process that works in the same way due to the Coriolis effect and Ekman transport, but it occurs when the wind is blowing in the opposite direction along the coastline.

- In the Northern Hemisphere, if the coast is on the east side, the open ocean is on the west side, and the wind is blowing from south to north, the wind pushes the water to the right, causing the surface waters to pile up against the coastline as the wind blows.

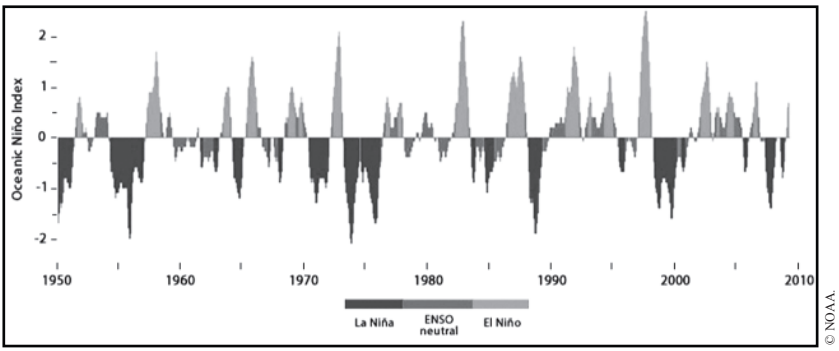
- The surface waters don't actually pileup; they are actually forced to sink because there's nowhere for them to go. They depress the thermocline and push the pycnocline down, which can suppress primary productivity.

- The surface waters are rich in oxygen because phytoplankton makes oxygen, but the deep waters are depleted in oxygen. Downwelling mixes the oxygenated-rich surface water into the deep water. Oxygen is an important nutrient for all the organisms that are in the deep pelagic and benthic zones of the ocean.

El Niño

- Upwelling and downwelling also has pathological effects, especially with the phenomenon called El Niño or, oceanographically, the Southern Oscillation.

- In the 1890s, Peruvian fishermen noticed that in certain years there was the arrival of an unusually warm current on the coastline. It happened to come typically around Christmastime, so they started to call it the Corriente del Niño, meaning the current of the Christ child in Spanish. In those years, their fisheries failed.



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In 2009, El Niño spread across the Pacific Ocean and hit the Peruvian coastline, damaging the fisheries there.

- The bird guano (fertilizer) industry was strongly affected during the El Niño years. The fisheries were no good, the guano was no good, and the local economy would crash. In fact, especially in earlier times, the whole region would go into a state of potential famine because of the lack of food.

- In a normal year, the surface winds are strong, so they create equatorial upwelling and blow the equatorial currents strongly over toward the western Pacific.

- Meanwhile, there's been strong upwelling off the Peruvian coast because the water is pulling away from the edge of the continent. The Peru current is coming from the south, so great upwelling is occurring, leading to happy fish, happy fishermen, and happy guano miners as a result.

- In an El Niño year, the fisheries fail because of an atmospheric phenomenon that is a persistent high-pressure zone in the tropical western Pacific. That change to a high-pressure system is called the Southern Oscillation.

- Because winds blow away from high pressure toward low pressure, the trade winds weaken and die out. The water moves back across the Pacific and suppresses the upwelling on the Peruvian side; in fact, downwelling is generated in the other direction on the Peruvian side.

- The strongest El Niños have been in recent times—specifically, in 1982–1983 and 1997–1998. One of the best-recorded occurrences was a more recent one in 2009–2010.

- Some of the effects of El Niño and the Southern Oscillation are sea level rises in the eastern Pacific by as much as 20 centimeters; water temperature rises by up to 7°; more evaporation occurs; low pressure intensifies over the eastern Pacific; and heavy precipitation often occurs in coastal South America along with torrential rains and landslides.

- All around the world in the trade-wind belts, there are major modifications due to El Niño that affect the amount of rainfall. El Niño has caused major droughts in Africa and in India at times, while causing torrential rain in other parts of the world—all disrupting local climate and local economic activity in many cases.

- Eventually, the reestablishment and redevelopment of equatorial upwelling occurs in a process called La Niña, which is the absence of an El Niño—or the opposite effect of an El Niño.

- In a La Niña year, there are very dry, sometimes very drought-like conditions across the southwest and California. There are more effects all over the world, in fact.

- The NOAA, the National Oceanographic and Atmospheric Administration, keeps the Oceanic Niño Index (ONI), which is a record of sea-surface temperatures measured in a particular place in the central Pacific Ocean.

Important Terms

downwelling: The movement of surface water downward, depressing the thermocline due to either high density or Ekman-transport effects.

equatorial divergence: The tendency of wind-driven surface waters to move in opposite directions just across the equator because of the opposite Coriolis effect in the Northern and Southern hemispheres.

upwelling: The movement of cold, deeper water upward to the sea surface when surface waters are drawn away by divergence or Ekman-transport effects.

Suggested Reading

Fagan, *Floods, Famines, and Emperors*.

Nash, *El Niño*.

Questions to Consider

1. How might upwelling at the surface influence the pattern of sediment types that are deposited on the ocean floor? (Hint: Think biogenous sediments and where you might expect to find more of them than other places.)

2. Could El Niño also have an effect on equatorial upwelling in the Pacific Ocean, besides the effect on coastal South America, based on the mechanism of how it is thought to be generated?

The Deepest, Slowest River—Polar Bottom Water

Lecture 32

Most of the volume of the ocean participates in very slow deepwater circulation driven by density differences called thermohaline circulation, which depends on temperature and salinity variations. Cold, salty water formed in the northern and southern polar regions sinks to form deepwater masses and spreads throughout the entire ocean. Flow is very slow relative to surface currents but involves enormous masses of water and is responsible for the global-scale mixing of the ocean. Surface currents and deep circulation together make up the global conveyor belt for water and heat in the ocean.

Deep-Ocean Transport

- Ocean circulation at the grandest scale is the circulation that occurs in the great bulk of the water that represents the deep ocean.

- The ocean is stratified, or layered, with the main boundary being the thermocline—the difference between the warm surface waters and the cold, deep waters. Stratification also indicates a density difference.

- Most of the volume of the ocean participates in a very slow and even majestic deepwater circulation. It takes place in specific patterns that are driven by the atmospheric circulation on the planet, the climate, the differences between the poles and the equator, and the Coriolis forces.

- The deep ocean is in motion due to—specifically and exclusively—density differences. Ultimately, it is gravity-driven flow; denser water sinks, and water that is not as dense rises.

- Density varies specifically with 2 major features: temperature and salinity, which is the amount of dissolved solids in the water. Water becomes denser as it becomes more saline, and colder water is denser than warmer water.

- Sometimes temperature is the dominant density variation in the water, and sometimes salinity is the dominant density variation—and sometimes it's a combination of the 2.

- **Thermohaline circulation** is heat-salt circulation. In fact, it's because those 2 things are the variables that govern density in the water that thermohaline circulation is density circulation.

Water Masses

- There are different water masses in the ocean. Even though the ocean is a fluid medium, there are still vast volumes, or parcels, of the water that acquire certain persistent characteristics.

    - Down to the beginnings of the thermocline, the surface waters exist from zero to about 200 meters.

    - Below that is the central water that extends from about 200 meters to the base of the thermocline.

    - Below that is a very important water mass called the intermediate water, which extends down to about 1500 meters.

    - From 1500 meters down to close to the bottom of the ocean is called the deep water of the ocean.

    - Below the deep water, there is a layer of water in some parts of the ocean called bottom water, which is water that is in contact with the bottom of the ocean and occupies the lowermost few hundred meters.

- Water masses form due to processes that occur exclusively at the surface. Even the water at the very bottom of the ocean acquired its characteristics—its density, salinity, and temperature structure—at the surface of Earth.

- The density-dependent layering of the ocean is a function of these different water masses. As water becomes denser or less dense, it sinks or rises until it's in some kind of equilibrium. Whenever water moves in the ocean, other water has to come in and fill in the space that it displaced.

- The surface water is the least dense, not surprisingly. It's typically warm water, and it's low in salinity because there's rainfall on the surface of the ocean that dilutes it.

- Conversely, the deep water is the densest, so it's very cold and very saline at the same time. It forms at the surface in high-latitude polar regions.

- The intermediate waters are intermediate in density and, therefore, intermediate in the salinity and temperature profile to the surface and deep waters. Intermediate waters also form at the surface but in very specific areas of the world's oceans.

- The cold regions, naturally, are the northern and southern polar regions. The water forms and sinks to form the deepwater masses in a downwelling process due to density differences. Ultimately, from the polar regions, the water spreads throughout the entire ocean.

- In the areas off Antarctica in the Arctic Ocean, the air temperature is cold; the ocean is losing heat to the atmosphere, so the water is getting colder, which is making it denser. At the same time, sea ice is forming.

- When water freezes and ice forms in the ocean, it makes freshwater ice. If the ice that has formed floating on the ocean surface is freshwater, then it has excluded the salts that were in that volume of water that turned into ice. Therefore, adjacent water around the ice has to take up those excess salts. The water becomes more saline and colder, which causes that water to sink.

- As that water forms, it sinks down and starts to spread through the ocean. This process is the basis for a conceptual model of pure thermohaline circulation.

- If water sinks, it has to be replaced, so the surface water is drawn northward or southward from the equator. Therefore, water has to well up in equatorial regions.

- This conceptual model of pure thermohaline circulation is a major part of the heat transfer from equator to pole on the planet that smoothes out the temperature differences between equatorial regions, which have an excess input of heat, and polar regions, which have a deficit of input of heat.

Deep-Measurement Methods

- Physical oceanographers measure the complicated temperature-depth-salinity profiles of the ocean using the CTD, the conductivity, temperature, depth profiler that has Niskin bottles attached to it. Many different bottles are lowered off the ship and are triggered at different depths to sample the water's chemistry.

- Swallow floats drift along with the currents, and they have sonar paintings that send their data out to a ship with a sonar sensor on the bottom of the hull that constantly receives data.

- A more sophisticated sensor system is something called an **Acoustic Doppler Current Profiler (ADCP)**, which can make a profile of the speed of movement of the water at different depths from the surface.

- In addition, gliders such as the Slocum glider are autonomous devices sent out in the water that can measure and then come to the surface and beam their data to satellites.

- There was a major program in the 1990s called the World Ocean Circulation Experiment that revolutionized our knowledge of deep circulation with millions of measurements.

- Today, the Ocean Observatories Initiative promises to put sensors on the ocean floor and in the water looking up through the water column that send data through fiber-optic cables to land so that real-time measurements can be kept.



© NOAA.

Using Niskin bottles, oceanographic ships generate temperature and salinity profiles at given locations and depths.

- Another method uses chemical tracers in the water. In the 1950s and 1960s, it was the atmospheric nuclear bomb–testing era that generated a large amount of the isotope tritium, which has a half-life of 12.5 years.

- For a long time, water samples were taken and the amount of tritium was measured, which could be used to determine the signature of water that had been at the surface and had been displaced in the deep subsurface.

- Today, chlorofluorocarbons that were released through the industrial production of CFCs are being used as deep-ocean tracers.

Antarctic Bottom Water and North Atlantic Deep Water

- As the sea ice forms off Antarctica, it leaves behind the coldest and highest-salinity water in the ocean. It obtains the salinity of about 34.8/mil and a water temperature that is below zero. Because it is saline, it can get down to –1/2°C. It's forming at a prodigious rate, with 20–50 million cubic meters forming every second off Antarctica.

- The sea ice rapidly sinks off the Antarctic shelf and down the continental slope. It's so dense and so cold that it sinks all the way to the bottom of the ocean and then spreads along the ocean floor, hugging the ocean floor of the Atlantic all the way to the equator in the widest and slowest-moving river on the planet. It takes about 500 to 1000 years to reach the equator while travelling at a rate of 10–20 kilometers per year.

- The North Atlantic also generates cold, deep water of similar salinity—34.9/mil. It generates water that's a little bit warmer at 2–4°C, which sinks and moves southward. **North Atlantic Deep Water** comes in and layers on top of the **Antarctic Bottom Water**.



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Niskin bottles are lowered off ships and are triggered at various depths to obtain samples of ocean water.

- Most of the bulk of the Atlantic water in the ocean is made up of North Atlantic Deep Water.

- Intermediate water forms in a couple of different locations in the world ,and it's an important part of the overall mixing of the ocean—especially the mixing that governs how strongly stratified the thermocline is.

Intermediate Water

- Antarctic Intermediate Water forms near the continent of Antarctica and is at about 5°C and 34/mil. It is layered in a sort of tongue that sits on top of the North Atlantic Deep Water.

- In the Northern Hemisphere, a very important source of intermediate water is the Mediterranean Sea, which evaporates a lot of water, so the water is pretty salty at 37.3/mil—quite a bit saltier than the rest of the water in most of the ocean.

- The Mediterranean Sea is also pretty warm at 13°C. It comes out of the Strait of Gibraltar and mixes with some Atlantic waters. It sinks to about 1000 meters depth, and that's where it finds its buoyancy neutral point—its balance point—and spreads out.

The Pacific Ocean

- The Pacific Ocean doesn't have a significant source of Arctic cold water in the way that the Atlantic does because the Bering Sea and the Aleutian Islands form a shallow-water barrier.

- The deep water in the Pacific is the slowest-moving water on the planet, and the conditions are quite uniform below about 2000 meters. There isn't a real source for distinct intermediate water, so it has more of a less-featured, slow-steady gradient in the water.

- The water in the Pacific Ocean is the oldest water at depth, which is measured by the time since it left the surface region. This concept is related to the residence time of water in the ocean, which is how long it takes to come back to the surface water and acquire new characteristics. In the Pacific, the residence time is at least several thousand years.

- All of these deep circulatory systems in the ocean link up in some way with the surface currents. The surface currents and the deep circulation together make up what is called the global conveyor belt for water and heat in the ocean.

- Through the 1990s and into the 21st century, we have a much more nuanced and complex view of circulation within the world's ocean.

- The surface waters and the deep waters are circulating on very different kinds of timescales. There's only a limited amount of exchange between the 2 of them—especially from the point of view of deep water turning into surface water.

- Surface water acquires its characteristics in the tropics, generally where there's warm water and a lot of rainfall. Everywhere where it is warm, there's water slowly diffusing upward—about a centimeter per day.

- The equatorial and coastal upwelling zones also contribute to surface-water formation by bringing deep water up. The wind-driven downwelling zones bring shallow water down, and the mixing of these systems is occurring especially around the continental margins all over the world all the time in a complex pattern of exchange.

Important Terms

Acoustic Doppler Current Profiler (ADCP): A device that measures current speed by measuring the Doppler frequency shift of sound waves reflected back from particles in the water.

Antarctic Bottom Water: The coldest, saltiest, and densest water mass in the ocean that forms off the Antarctic continental shelf and spreads over the base of the entire Atlantic Ocean.

North Atlantic Deep Water: The cold, saline water mass that forms in the North Atlantic and Arctic oceans that is responsible for most of the volume of the deep ocean.

thermohaline circulation: Gravity-driven movement of deepwater masses due to the density differences controlled by salinity and temperature.

Suggested Reading

Garrison, *Essentials of Oceanography*, chap. 8.

Open University, *Ocean Circulation*.

Questions to Consider

1. Do you imagine that it is likely that Coriolis motions affect deepwater circulation? Why or why not?

2. What factors about deep circulation might allow water masses to retain their characteristics so persistently for even thousands of years?

The Ocean and Global Climate

Lecture 33

Earth's climate is a balance among solar radiation, the redistribution of heat by ocean and atmosphere, and the natural greenhouse effect that traps heat due to the chemical composition of the atmosphere. Most of the heat in the climate system is stored in the ocean. Water vapor, carbon dioxide, and methane are the main heat-trapping gases in the atmosphere responsible for the greenhouse effect; without them, Earth would be a frozen wasteland. Ice and sediment cores are records of the past climate and show how rapidly Earth's climate has changed through time.

Earth's Climate System

- The natural state of Earth's climate is a balance among solar radiation as the heat and energy input, the redistribution of that heat by the ocean and the atmosphere, and the envelope of the atmosphere itself, which contains the naturally occurring greenhouse gases that make up the chemical composition of the atmosphere.

- The ocean plays an absolutely central role in the maintenance of the overall thermostat and climate control of the planet due to its tremendous heat capacity.

- The oceans contain the vast majority of the overall heat in the ocean-atmosphere system; the oceans are the great heat sinks for the planet.

- The Sun shines down on the planet and warms it, but an equal amount of heat is radiated back to space. The planet surface overall is in a balance; it has a heat budget, and the budget is balanced.

- The heat that's radiated out to space has to exactly equal the heat that's coming in—or else the planet would slowly (or rapidly) warm up, or it would slowly (or rapidly) cool down. Over millions and millions of years, it has maintained equilibrium.

- Of the incoming solar energy, 31% of it reflects back off of the atmosphere. Basically, clouds are reflective, and the light immediately bounces back into space. **Albedo** is a measure of how reflective the surface is.

- In addition, 47.5% of the incoming solar energy is absorbed at the surface of Earth and ultimately gets reradiated back as heat instead of light, so it warms things up and radiates into the atmosphere.

- Almost all of the remaining balance, 17.5%, is absorbed within the atmosphere directly.

The Natural Greenhouse Effect

- The **greenhouse effect** is the fact that certain gases in the atmosphere are able to absorb heat and basically maintain that heat. The atmosphere doesn't radiate through those gases; instead, it heats them up.

- Water vapor is the primary greenhouse gas on the planet. The atmosphere can take up to 4% water to get to high humidity.

- The second greenhouse gas that's important is carbon dioxide, which occurs in very small amounts—much less than 1%—but it absorbs heat very efficiently.

- The other important greenhouse gas is methane, which is naturally emitted by the planet due to biological processes—specifically, the decomposition of living things.

- Currently, Earth's average surface temperature is between 15°C and 16°C—or 59°F and 60°F—which is a reasonably comfortable average for life.

- If there were no water vapor, carbon dioxide, or methane in the atmosphere and no ocean on the planet—no giant heat trap—people have calculated that the actual surface temperature of Earth on average would be about –18°C, or just below 0°F.

- On our planet, the day-to-night range is just a few tens of degrees, and the annual range from winter to summer—even in the high latitudes—is measured in tens of degrees and not hundreds. That's a good thing.

- Life depends on the greenhouse effect in the sense that if it weren't occurring, the world would be frozen over. We wouldn't be able to live here; there wouldn't be any free water present.

- In 1824, French mathematician and physicist Joseph Fourier recognized the fundamental heat-trapping nature of Earth's atmosphere.

- In 1857, British physicist John Tyndall demonstrated the atmospheric greenhouse effect quantitatively through experiments and identified the specific gases carbon dioxide and water vapor as the key gases that played the role in generating this greenhouse effect.

- By 1896, Swedish chemist Svante Arrhenius proposed that the burning of fossil fuels—coal in particular—would increase the amount of carbon dioxide in the atmosphere, trap heat, and prevent the next ice age.

- In 1906, Arrhenius calculated the warming effect of a doubling of carbon dioxide as 1.6°C or more. He thought that this would take 3000 years, but we're actually approaching the doubling level already. It won't be that many more decades before we reach the doubling level—at least at current rates of increase of carbon dioxide in the atmosphere that are being measured today.



© U.S. Geological Survey/Dave Harlow.

In the 1990s, Mount Pinatubo erupted in Indonesia and put massive amounts of dust and sulfur dioxide into the stratosphere.

Natural Climate Change

- Climates certainly change. The ice ages are examples of long-term scales of climate change, but there are also short-term scales such as the medieval warm period—a period in the middle ages when Europe enjoyed especially clement weather.

- There was a period in the 1700s of the Little Ice Age, when the climate was especially cold and harsh in Europe and even in North America.

- Large-scale volcanic eruptions, such as Mount Pinatubo in Indonesia in the 1990s, put massive amounts of dust and sulfur dioxide by way of the ash that comes out of the volcano into the stratosphere. These eruptions reduce warming over a period of time, and the global climate and global temperatures take a noticeable dip.

Measuring Long-Term Climate Change

- How do we know about longer term climate change, such as the changes between the ice ages and over the past million years?

- The fundamental record for long-term climate change are ice cores—particularly those from Antarctica and Greenland—which provide data for over 600,000 years on temperature and on the content of the atmosphere at any given time in history or prehistory.

- The record that comes from ice cores shows that there's been a cyclicity of changing parent surface temperature of the atmosphere in which the rise and fall of temperature exhibits a gradual growth of the glaciers and ice sheets and a cooling of the atmosphere—and then a sudden drop-off coming out of each glacial period.

- Currently, Earth is experiencing an interglacial period. There have been major glacial periods, and the carbon dioxide and temperature in the atmosphere and the apparent sea level have increased and decreased together. There is a linkage between these systems.

- Sediment cores from the ocean floor also provide a record that goes back much farther in geological time—before there were any glaciers on the planet.

- Oxygen isotopes and other proxies show us what the temperature conditions of the ocean were at different times. There were periods that were much warmer than today, and they were associated with different chemistries of both the ocean and the atmosphere. There were also periods that were much cooler during the glacial stages.

- We can obtain a much longer-term record in the ocean-floor sediment cores than we can obtain from the ice cores.

Modern-Day Global Warming

- We hear about the atmospheric warming, but we don't hear about the ocean warming as much because that's quite well known now. The measurements are robust and can be shown from many different kinds of data—from both surface and satellite measurements. In fact, ocean heating is actually taking up most of the change in heat on the planet.

- The climate system is going through a modification that is different from what was happening prior to the late 1800s with a signal that started to strongly emerge in the early part of the 20th century.

- The heat content of the ocean is rising rapidly, and it is a reflection of the excess temperature in the atmosphere on the land surface and at the ocean surface.

- We also know from measurements that were made starting in the 1950s that the concentration of carbon dioxide in the atmosphere has been rising over time. At no time from the geological record in the last 10 million years has the concentration been as high as present-day levels.

- Temperature and carbon dioxide levels are changing in lockstep on the planet. That's one of the fundamental observations that causes people to draw the conclusion that the change in temperature that we observe on the planet is related to the change in the amount of carbon dioxide in the atmosphere that's being put there by the burning of fossil fuels—as noted by Arrhenius in the 1800s.

- The atmospheric level of carbon is changing. Carbon dioxide has changed from a preindustrial level of 280 parts per million to a level of 390 parts per million in 2010.

- Methane is another greenhouse gas that is going into the atmosphere at greater rates, and this is primarily due to agriculture.

- Besides the greenhouse heat-retaining effect, carbon dioxide plays a huge role in the ocean system: The more carbon dioxide that gets dissolved in the ocean, it has an effect on the chemical balance of the ocean, which is detrimental for much of the life that's present in the ocean today.

The Ozone Layer

- The ozone layer story is kind of salutary because it shows that there can be successes in global-scale modification of what we do chemically to the atmosphere.

- In 1990, there was an international agreement to ban CFCs, and it seems to be working.

- The concentration of chlorofluorocarbons in the atmosphere is declining rapidly. The ozone depletion has flattened out from a very rapid change and may reverse soon.

- Maybe this is a model for global-scale cooperation on carbon emissions and the change in the natural state of the climate system that is represented by additional heat-trapping gases going into the atmosphere today.

- On the other hand, there is the possibility of finding ways to chemically remove carbon dioxide from the atmosphere by a process called carbon sequestration.

Important Terms

albedo: The fraction of solar energy reflected by a surface (as opposed to energy absorbed).

greenhouse effect: The physical property of some atmospheric gases to absorb and trap heat from the Sun's radiation shining on Earth.

Suggested Reading

Broecker, *How to Build a Habitable Planet*.

Murphy, *To Follow the Water*.

Questions to Consider

1. The average temperature of the ocean as a whole is just a few degrees above freezing. Given that, how is it that most of the heat in the climate system resides in the ocean?

2. Based on what you know about water and heat capacity, if the concentration of greenhouse gases in the atmosphere somehow suddenly returned to preindustrial levels, how rapidly or slowly might the global ocean heat content return to previous levels as well?

The Warming, Rising Sea

Lecture 34

The global warming phenomenon is a modification of the natural greenhouse system due to the rapid addition of carbon compounds to the atmosphere over the past 150 years, primarily from the burning of fossil fuels. The link between carbon dioxide, methane, and greenhouse warming has been known for over a century. About 80% of the extra heat retained through anthropogenic greenhouse warming is stored in the ocean. Effects that are already in existence include sea-level rise, changes in ocean acidity, and loss of sea ice—especially in the Arctic region.

Heat Content of the Ocean

- The largest effects of the modified heat-trapping nature of the atmosphere from the increased carbon dioxide content are already being seen in the ocean and are probably going to continue to be seen in the ocean.

- The heat content is rising in the ocean at an accelerating pace, and it's going to have an effect on all sorts of aspects of the ocean as a whole—from sea level to the movement of ocean currents over time.

- Future decades are likely to see the rise of heat content accelerating in nature and in intensity. The first most important change that we're seeing on the planet is that global-scale sea level, or the eustatic average, is clearly rising.

- From 1930 to the turn of the 21st century, the sea level has been rising at an average rate of about 1.8 millimeters per year.

- Once there was satellite data that could measure the height anomalies in the sea surface directly, it became possible to calculate sea-level change with even greater precision.

- For the period from 1993 to the end of 2008, the slope of the curve showing change in sea level shows about 3.1 millimeters per year of sea-level change—a much steeper slope than it had been.

- Sea-level rise closely tracks the overall global average temperature rise over time. When the global temperature increases, land ice starts to melt. Glaciers are currently in retreat on the planet.

- Even more importantly, the Greenland Ice Sheet is one of the major ice caps of the planet, and if it melted, sea level would rise tremendously.

- Greenland and Antarctica are losing volume; they're losing land ice, and it's turning into water. That water is being introduced into the ocean as new mass, so there's an increase in the volume of water in the ocean.

- The sea-level rise is also partly due to the **thermal expansion** of the water. As the water heats up, the water gets a little bigger, filling the basin a little higher than it did before.



© Patrick Kelley, U.S. Coast Guard.

Since the 1970s, there has been a rapid decrease in the amount of ice in the Arctic due to the addition of carbon dioxide to the atmosphere by humans.

- Of the overall change in sea level—at least 3.1 millimeters per year—about 2/3 is the effect of land ice melting and about 1/3 is thermal expansion in that short window of time (from 1993 to 2008).

- The ocean is a great heat sink, and 80% of the heat comes from the contribution of anthropogenic carbon dioxide that's added to the atmosphere through human activity that makes it into the ocean.

- Probably the most significant effect of carbon dioxide being added to the atmosphere is the warming of the Arctic region; in particular, the annual melting of sea ice in the Arctic Ocean is rapidly increasing.

- The reduction of sea ice is a problem for many of the organisms that live in the Arctic Ocean that depend on the sea ice. There are a number of Arctic marine ecosystems that are dependent on sea ice being present on top of the ocean to provide various habitats and to limit the amount of water mixing and wave action.

Projections of Earth's Future Climate

- At the current rate of change, by about 2030 the sea ice is projected to be less than 1/3 of its average level that existed during the 1979–1990 time period.

- In 2007, for the first time ever, navigable waters for ships that were not icebreaker-class ships, which are ships that are specifically designed to be able to cut channels through ice, opened up through the Arctic Ocean.

- When the Arctic sea ice melts, the freshwater will return to the ocean, but it won't change sea level directly. More importantly, the melting of sea ice contributes to a positive feedback in the ocean-climate system—and that is the albedo change.

- When you melt ice and turn it into open water, then more energy is absorbed from the Sun, and that warms the water up more, which can feed back into melting more ice. Therefore, there's a positive feedback in which melting the ice warms the Arctic Ocean, which causes more ice to melt—and the process continues. It's pretty clear that this process is under way in the Arctic already.

- Land ice can contribute to sea-level rise because it adds water that was on land to the ocean. This change in land ice is dominated by Greenland and Antarctica: Approximately 50%–80% of the total sea-level rise that comes from ice melting is coming from Antarctica and Greenland together, but Antarctica in particular.

- The present-day sea level is near the highest it's been over all the glacial and interglacial cycles. There's only been one point in the last 250,000 years during which sea level was higher than the present-day level.

- The melting of the sea ice and the partial—not complete—melting of some of the polar icepacks could induce and ultimately raise sea level 4 to 6 meters, or even more if the land-ice melting goes even further than expected.

- Besides sea level, the salinity in the ocean is also starting to be modified by this whole process of melting sea ice.

- If ice melts and is put back into the ocean as freshwater, it's going to cause the surface waters in the Arctic region, the region off Greenland, and the region in which the North Atlantic Deep Water forms to become fresher.

- As a result, deepwater formation could begin to slow down and could begin to go into a new state in which it's not being generated as robustly as it is today.

Modeling Earth's Climate

- One piece of somewhat good news from climate modelers is that current models suggest that the likelihood that this freshwater effect could be so strong as to significantly impact the Gulf Stream, change the climate in Europe, and paradoxically throw it into a new ice age looks very unlikely.

- In order to project into the future, we have to start to speculate more, and the way that scientists speculate is to run numerical models—global-scale computer simulations of the climate.

- Scientists use the best-available physics and understanding of how the ocean and the atmosphere flow, interact, and respond to heat input in order make the best projections. They use the biggest computers in the world to run what are called **general circulation models**, or GCMs.

- All the simulations suggest that if we stopped emitting carbon dioxide today, what's already in the atmosphere and what's already in the ocean in terms of the heat is going to continue to warm up the planet, raise sea level, and have other effects over the span of the next century. Any additional carbon dioxide that we put into the atmosphere is simply an additional factor in that future rise.

- Based on current projections, the global average surface temperature will increase between 1.1°C and 6.4°C by the end of the 21st century—exceeding the total amount of change since the last ice age to the present day.

- GCMs suggest that the rate of warming is likely to be unprecedented. The rates of warming and of sea-level rise are both already increasing faster than the last IPCC median values, or the middle values, of all those computer simulations.

Effects of Sea-Level Changes

- One of the biggest effects of sea-level rise is that low-elevation regions are at risk of losing populated area.

- For coastal regions in a large area such as the United States, people may have to retreat from the coast as the sea continues to encroach upon their homes, or they may be forced to build very expensive seawalls.

- The effects are even more dramatic for countries in the world that have no place to go—no higher ground to go to—including island nations in the Pacific and Indian oceans and Bangladesh.

- For example, Kiribati and the Maldives, which have populations of hundreds of thousands of people, are Pacific atolls that have an elevation of 1.5 to 2 meters above sea level. Projections seem to suggest that in a matter of decades—not centuries—these countries may be uninhabitable.

- In Tuvalu, another Pacific atoll, the highest elevation in the entire country is only 4.5 meters above sea level. A 20- to 30-centimeter sea-level rise would be enough to make the whole country uninhabitable.

- A 1.5-meter sea-level rise—something that we could see in a couple of centuries or maybe even in the next century—would place 16% of Bangladesh under the tidal range and would displace 17 million people.

- According to ocean climatologists, El Niño periods have already become more frequent since the 1970s. There's some evidence that cyclonic storms, hurricanes, and typhoons are becoming more severe—and possibly even the extratropical cyclones, although that's a little less certain. The reason they're becoming more severe, in the case of tropical storms, is that they're fueled by heat.

Important Terms

general circulation models: Supercomputer simulations of the circulation of heat and compounds in the ocean-atmosphere system; used to simulate climate fluctuations and long-term trends.

thermal expansion: The increase in volume of water as it becomes warmer; specifically used to refer to the component of sea-level rise due to this effect as heat content of the ocean changes.

Suggested Reading

Climate Change 2007.

Pilkey and Young, *The Rising Sea*.

Rogers and Laffoley, "International Earth System Expert Workshop."

Questions to Consider

1. If all the ice in the Arctic melts, what effect might that have on North Atlantic Deep Water mass formation?

2. Can you think of other examples (besides sea ice and albedo change) of possible positive or negative feedback in the ocean-climate system?

Marine Pollution—The Impact of Toxins

Lecture 35

Human activity is so pervasive that it increasingly has impacts that can be seen all over the world ocean. Oil spills can be locally devastating but tend to be of limited extent and are now much less frequent. Plastic garbage in the sea has become pervasive and can be disruptive to marine life. Ocean acidification from the carbon dioxide humans add to the atmosphere is a form of pollution that has the potential to greatly alter marine ecosystems. Heavy metals and chemical pollution are increasingly problems from industrial runoff, and bioaccumulation causes a health risk to humans.

Human Impact on the World's Ocean

- Marine pollution is the introduction into the ocean by humans of any kind of substances—or even energy—that changes the quality of the water or affects the physical and biological environment.
- Pollutants, by definition, interfere in some way with reproductive, metabolic, or other biochemical processes of life in the sea.
- Solid waste that is dumped at sea still occurs to a great extent, both from sources on land and also from marine dumping from ships.
- Runoff of agricultural waste and industrial waste come through the air in the form of particulates from burning coal that land on the surface of the ocean. These occurrences are introduced less intentionally but are still a result of ordinary practices. Oil spills at sea are another example.

Carbon Dioxide as a Toxic Compound

- One of the fundamental stresses on the planet is energy pollution. The warming of the water can be heat pollution that causes higher water temperatures, which has a toxic effect on many of the different organisms in the sea.

- Coral reefs are the most specific example of energy pollution. When the sea-surface temperatures exceed normal high temperatures for summer by only about 1°C, the corals respond by expelling symbiotic algae that live within the coral polyps, the zooxanthellae, which leads to a process called coral bleaching.

- The worldwide coral population for the number of coral reefs that are healthy today is only about 50% of what it was 50 years ago.

- The introduction of carbon dioxide into the environment creates another form of pollution called **ocean acidification**, in which most of the carbon dioxide that has been introduced into the atmosphere has been exchanged with the ocean and has become dissolved carbon dioxide in the water of the ocean. Dissolved carbon dioxide makes water more acidic because it reacts with the water to form something called carbonic acid.

- A small change in the alkalinity of the water—from a pH of 8 down toward the direction of more acidic—interferes with the corals' ability to make their shells.

- The pH of the ocean today in the tropical regions is about 8.1, and its preindustrial level was about 8.2, which is known from old water samples. If the pH of the ocean changes to 7.9—which is not a huge change, but a pH scale is a logarithmic scale—it's possible that the corals will cease to be able to make their skeletons, causing them to be unable to build a reef at all.

- At present rates, the pH of the ocean is projected to drop to 7.9 in the next 40 years. A near-extinction of many or even nearly all reef-building corals is considered a real possibility by marine biologists.

- Other organisms are at risk, too, as a result of acidification because there are many organisms that make their shells or skeletons out of calcium carbonate.

- More generally, it's simply not known how the larval stages of many organisms will respond to a changing pH balance of the water in which they live. This could interfere with a number of metabolic processes, so changing the fundamental acid chemistry of the ocean has a huge effect on oceanic life.

Toxic Marine Pollution

- There are many examples of the introduction of toxic materials—toxic to life in one way or another—into the sea, including point sources of sewage outfall. For a long time, raw sewage from all over the United States and, certainly, the rest of the world was simply dumped into the ocean.

- The key characteristics of any pollutant in the marine environment are the concentration of that pollutant, or the amount that's present; the **toxicity**, or the degree to which that particular pollutant is damaging; and the **persistence**, or the length of time that pollutant lasts in the environment.

- Runoff from land and the direct introduction of sewage outfall and of solid-waste dumping introduce a number of fairly toxic materials into the ocean.

- Examples of toxic materials include PCBs and heavy metals like mercury and lead, which are organic compounds that are used in industrial practices or in the dry-cleaning industry that interfere with various kinds of biological metabolic processes.



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For a long time, raw sewage all over the world was dumped into the ocean, which was viewed as the ultimate drain and sewer.

- Pesticides are delivered primarily from rivers and streams because they're put onto agricultural fields, end up in the hydrologic system, and flow down to the ocean.

- Very small concentrations of heavy metals can cause toxic damage to organisms. Among others, important heavy metals are lead, mercury, and copper.

- Chemical pollution by toxic heavy metals and organic compounds like PCBs has affected virtually all the urbanized coastal areas of North America and, in fact, such areas around the world.

- As a result of chemical pollution, shellfish have too much of the toxic compounds to even be consumed, and fisheries are banned for shellfish in many estuaries that were formerly highly productive.

- Mercury comes from the burning of coal and is a teratogen, meaning it causes genetic damage. Women who are pregnant are advised not to eat too much tuna because of the examples of the acute mercury toxicity that unfortunately have been seen in the world. Minamata disease is essentially acute mercury poisoning.

- In addition to tuna, the FDA recommends children and women of childbearing age to avoid swordfish, shark, king mackerel, altogether and to limit their intake of many other fish. These are all large fish that consume other fish; they're living at a high trophic level as consumers in the ocean.

Biomagnification

- In the late 1950s and early 1960s, DDT was being used very heavily to control mosquitoes and all sorts of pests. The problem is that DDT gets into ocean water at very low concentrations—approximately 3 parts per trillion—and is taken up from the water by plankton, which are then eaten by small fish.

- The amount of food that needs to be eaten at each trophic level is magnified by a factor of 10, beginning with the small fish, where the concentration of DDT is at 0.5 parts per million, all the way up to the larger fish and, ultimately, the birds that were consuming those fish at the fourth or fifth trophic level.

- In pelicans and cormorants, DDT concentration is at 25 parts per million. It's toxic to human beings if we consume animals in high trophic levels, such as tuna and swordfish.

- **Biomagnification** applies to many pollutants, not just to DDT; it applies to mercury, PCBs, and other chlorinated hydrocarbons.

- Dolphins off U.S. coasts have been found to have flesh that had 6900 parts per million PCBs. The human safe limit set by the FDA is 5 parts per million, so those dolphins are essentially toxic substances because of PCB dumping in the ocean.

- Lead is another substance that becomes concentrated through biomagnification.

- There is some good news on these kinds of toxic substances because the recognition of their toxicity and accumulation in ocean water, sediments, and organisms has led to real action.

- In other parts of the world, toxic substances may not be controlled as well. In many developing countries, what goes into the ocean is virtually unknown and uncontrolled.

- Nutrient runoff into the ocean is a form of pollution that can be too much of a good thing. **Eutrophication** is the result of putting excess nutrients in the water, and it causes too much to grow in the water.

- Nutrients enter the water from either sewage outfall or agricultural runoff of fertilizers, causing massive booms of algal plankton such as red tide and yellow foams.

- Red tide is the massive bloom of dinoflagellates, which are photosynthesizing phytoplankton. In high concentrations in the water, they become very toxic to marine life. They can kill a lot of marine life and can sicken or even kill human beings who consume that marine life. Red tide can get so bad that it can even be seen from space, as in satellite images of the Florida peninsula.

- Black tide is a massive bloom of algae in the water that is fed by nutrients from runoff in eutrophication. It's not directly toxic itself, but it uses up the available oxygen.

- The effect of hypoxia, or low levels of oxygen, is that the large fish and shrimp that can move will leave the area and go to where there's more oxygen. Other organisms that can't leave the area or that don't move as fast, such as crabs and shellfish, will suffocate.

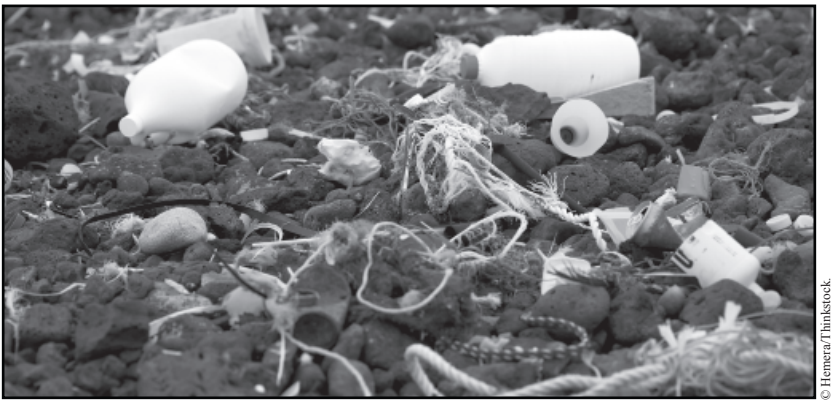
- In the Gulf of Mexico, there's something called the dead zone. From February through late summer every year, a huge **hypoxic zone**, or low-oxygen zone, appears in the Gulf of Mexico off the mouth of the Mississippi River.

- One of the maybe positive aspects of the dead zone—in terms of the eutrophication problem at least—is that it's pretty reversible because of the direct influx seasonally of this essentially toxic nutrient load into the water.

Solid Waste in the Sea

- Another form of direct dumping into the water is solid waste. The sea is a dump for trash and garbage all over the world. Restrictions are growing on this kind of dumping, but it's still a big problem.

- Military dumping of solid waste has been going on for a very long time and is restricted now. At the end of World War II, the navy had large stores, many barrels, of mustard gas that had been stockpiled during the war and never used, and they dumped these into the deep water of the ocean. There are huge dumps like these all over the world's ocean.



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When garbage is incinerated, chemicals are released into the atmosphere that often end up on the land or in the sea.

- Plastic garbage and particles in the sea have become pervasive. Every year, 135,000 tons of plastic are dumped by ships at sea, including fishing gear that cripples or kills marine mammals. These are very real and growing problems.

- The Great Pacific Garbage Patch is a region of the North Pacific Ocean within the big gyre in which there is an estimated 1 million pieces of plastic per square kilometer over an area that in aggregate might be as large as the continental United States.

- One sampling study of the water in the Great Pacific Garbage Patch showed that the actual plastic particles outweighed the zooplankton in that region by a factor of 6.

- Plastic ingestion by pelagic birds is a major problem. Pelagic birds such as albatrosses and fulmars are found in recent years to have up to 20 or more pieces of indigestible plastic in their stomachs, interfering with their digestive systems.

- These conditions have been found in organisms living in the Pacific and Atlantic oceans and have recently been discovered in fulmars living in the Arctic Ocean region.

Sound Pollution in the Sea

- The industrialized ocean is a very noisy place. Ships use sonar, and seismic reflection exploration below the ocean floor uses air guns that emit loud booms into the water. Most of all, everyday shipping is a constant source of noise from propellers.

- The potential impacts are large for animals that use echolocation and sound to communicate, such as whales and dolphins.

- For the strongest sounds, there is possible damage to internal organs of mammals that use echolocation. Maybe only high-powered navy sonar can do this, but the research is ongoing.

Important Terms

biomagnification: The exponential increase in the concentration of toxic compounds in animal tissues at successively higher trophic levels.

eutrophication: Conditions of overabundance of nutrients in the water usually due to fertilizer runoff, leading to harmful algal blooms and hypoxia.

hypoxic zone: Any region in the ocean of extremely low oxygen availability due to fertilizer runoff; an example is in the Gulf of Mexico off the mouth of the Mississippi River.

ocean acidification: The increase in acidity of seawater that is developing as a result of increased dissolved carbon dioxide.

persistence: The length of time a pollutant lasts in an environment.

toxicity: The amount of a pollutant necessary to cause some form of damage in an ecosystem or organism.

Suggested Reading

Clark, *Marine Pollution*.

Ebbesmeyer, *Flotsametrics and the Floating World*.

Questions to Consider

1. How is ocean acidification connected to—but a completely different effect from—ocean warming?

2. It was often said in past decades that "the solution to pollution is dilution," and the ocean is very big, so it could dilute toxic compounds. Why does this not work for many compounds, such as mercury or PCBs?

The Future Ocean

Lecture 36

The ocean is constantly changing, and human activity is accelerating those changes. Recognition of human impacts has led to important steps to maintain the long-term chemical and physical balance, stability, and ecosystem health in the ocean, but challenges abound. Marine conservation areas permit refugia for fish to spawn and populations to recover. Increased international agreement on what should be done in the open ocean away from territorial boundaries may help in achieving sustainable yield levels. Heat input from global warming, rising sea levels, and acidification from carbon dioxide will modify the ocean environment in specific ways, presenting challenges for societal interaction with the global ocean.

Change Is Constant

- The ocean is changing over so many different timescales—from human timescales and seasonal cycles of phytoplankton to geological timescales of plate tectonics. Human activity is accelerating those changes, possibly even on those much longer timescales.

- Approximately 41% of ocean areas are strongly affected by multiple impacts, especially overfishing, toxicity, and coral bleaching. That's a huge area of the surface of Earth.

- The activities of human beings are pushing the ocean environment to change more rapidly. Ecosystems are changing much more rapidly than they should naturally because human beings are fishing out lots of the top predators, for example. Coastlines are changing more rapidly because of warming and rising seas.

- It's more difficult for the natural ecosystems to respond in an environment where human beings are trying to maintain certain aspects of the environment.

- Today, there are ongoing studies of coral reefs that look at how they're colonizing areas farther and farther north as the water begins to get warmer. In some cases, they seem to be successful, but in other cases, they don't seem to be keeping up.

- Human beings are removing the top predators and are causing pollution and other upsets to ecosystems that can cause whole systemic collapses of these ecosystems.

- Today, the rate of species extinction appears to exceed anything since the last of the great mass extinctions.

- In a book called *A Sea in Flames*, marine ecologist Carl Safina draws some really interesting conclusions one year after the 2010 Deepwater Horizon oil spill in the Gulf of Mexico.

- For example, Safina saw that when the spill occurred, fishing and shrimping were banned for a period of time. This action likely helped the wildlife in the Gulf more than the spill hurt it because without the shrimping, there was more food in the food chain for all organisms, giving them a chance for their populations to recover. Paradoxically, it was a good year for growth for the marine wildlife in the Gulf.

- The chronic and systemic effects human beings have on the marine ecosystem far outweigh the damage done by singular events like the oil spill in the Gulf of Mexico. Fertilizer runoff in the dead zone, for example, does far more harm than one oil spill.

- Even compared to 50, 70, or 100 years ago, our impact on the ocean is fundamentally different because there are so many more people trying to derive food from the ocean; having an impact in terms of what is put into the sea; pulling oil and gas out of the ocean floor; and driving ships around on the surface, putting sound pollution into the water and affecting marine ecosystems.

Human Impact

- The impact of human beings is pervasive because we've become pervasive, and we've only become pervasive in the most recent times in both human and geological history. We dominate the planet now, including the ocean.

- We've eaten 90% of the large fish in the sea in 50 years. We've lost nearly 1/2 of the coral reefs on the planet, and we don't know whether they can come back or whether they will continue to perish.

- In about 150 years, we've built up the coastlines all around the world—rich and poor countries alike—and we've impacted all those coastal marine ecosystems and the physical environment of the coastlines in enormous ways.

- In 1960, aquanauts Jacques Piccard and Don Walsh went down in the bathyscaphe *Trieste* and visited the bottom of the Mariana Trench, the deepest place in the ocean—11,000 meters below the surface of the water—and stayed there for 20 minutes.

- Since 1960, no human being has ever been back down there. In fact, no human being has ever been back down anywhere in the bottom of the deepest regions of the ocean. It's the most unexplored part of the planet; 95% of the ocean floor has never been seen by human eyes directly.

- The great depths are still great unexplored environments, and at least on a relative scale, they're the places where we're having the least impact. Deep marine ecosystems are largely untouched and unaffected by human activities.

The Coming Decades

- In the coming decades in the ocean, the temperature and heat content of the water are going to increase, and sea level is going to continue to rise—perhaps at an accelerating pace. There's also going to continue to be the chemical change of the entire surface of the ocean in the form of acidification.

- With the input of freshwater in the Arctic and Antarctic regions from the melting of sea ice, there's a possibility that we may even modify the great oceanic conveyor belt.

- As terrestrial resources become increasingly stretched, we're going to see more utilization of the ocean. There's certainly going to be increased aquaculture of freshwater species and mariculture off shore. Therefore, the kinds of fish that we eat will become more and more fish that are farmed instead of fish that are wild caught.

- The industry pertaining to offshore oil and gas drilling—spills notwithstanding—is likely to continue. Probably, mining in the ocean will begin. New energy from the ocean may be a really important source.

- Wind power seems to be involved in the future of energy; windmills are already being placed off shore.

- Another new technique in the realm of energy is the use of tidal energy, or wave energy, which involves the placing of some sort of fixed structures mounted to the ocean floor—or perhaps even floating—that have turbines on them that will turn as ocean currents or tidal rush comes in and out of coastal environments.

- Wave energy, the ups and downs of the waves, is a form of energy that can be potentially tapped to generate electricity as well.

- Another interesting form of energy is called **ocean thermal energy conversion (OTEC)**. If you have an area where you can tap the deep water of the deep-sea environment, you can draw cold water up to the surface. Because of its temperature difference with shallow surface waters, you can drive heat exchangers, or turbines, that will allow you to pull the energy out of a difference in temperature between the surface and the deep water to make electricity.



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A large cargo ship that burns diesel is actually a very efficient, low-carbon way to move goods around the planet.

- One more use of the ocean that is going to continue to grow is shipping. Ships, per unit of good, only need to burn incredibly small amounts of fuel for safe transportation from Asia to North America. The carbon footprint of shipping is excellent relative to land transportation and can be even smaller for long-distance transport.

- Vast areas of the ocean have never been sampled to determine what's living out there. Sampling efforts begun by the Census of Marine Life must continue; there are still many tracts that are entirely unsampled. We still have an underexplored ocean.

- The idea of the Ocean Observatories Initiative is to put sensors both at the bottom of the sea and up through the water column and connect them to land with offshore fiber cables so that real-time data can be acquired.

- The Ocean Observatories Initiative includes autonomous underwater vehicles and buoys in various parts of the sea all over the planet. This initiative is going to be the future of oceanography, and in many ways, it's making our presence not just an expedition at a particular time, but all of the time.

The Coming Centuries and Millennia

- The effects of the enormous accidental geophysical experiment—the release of carbon into the atmosphere and ocean—are going to be felt for centuries, guaranteed.

- Plate tectonics will continue. Evolution will continue. The 4-billion-year-old waters will continue to crash on the shoreline. They'll move in currents and in thermohaline convection for many millions of years to come—whether we're here or not, in fact.

- We can come up with increased international agreement on what should be done in the open ocean, such as the efforts by the International Whaling Commission and the International Commission for the Conservation of Atlantic Tunas. There's a lot of controversy, but territorial waters near land and the more recent Exclusive Economic Zones that extend 200 miles from shore are already governed by international law of various kinds.

- We have to strengthen international laws to avoid the kind of tragic overfishing that's causing ecosystem collapse in the sea today, including the tragedy of the commons.



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Instead of taking up space on land, wind turbines can be placed in offshore regions as an alternative source of energy.

- Ocean resources, sea level, and general conditions are international goods for us, and they're also international problems.

- In order to protect something, you have to know about it. To avoid a destructive fate for the world's ocean, we have to first know the ocean realm.

- One hopeful sign is the establishment of marine sanctuaries and marine conservation areas by the United States and by many other countries around the world.

- In the oceans today, 0.8% is protected as marine sanctuaries or marine conservation areas. Perhaps that number should be more like 10%, 12% (the percentage of land protected in national parks worldwide), or 20% to provide enough refugia for the fish stocks to recover and for the ecosystems to thrive.

- The ocean is a vast and interconnected frontier; it is not only a food web, but also an interdisciplinary web in which all the sciences meet. To understand it—and to be good stewards—we have to view the ocean as a whole.

Important Term

ocean thermal energy conversion (OTEC): A pilot technology to generate energy by exploiting the temperature difference between warm, near-surface water and cold, deep water drawn up to the surface.

Suggested Reading

Earle, *The World Is Blue*.

Safina, *The View from Lazy Point*.

Questions to Consider

1. As humans continue to interact with the ocean ecosystem, what are some tenets or principles for more effective stewardship, without shocking economic activity?

2. In what ways is the ocean likely to remain unchanged by human activity (at least the activities we know about in the present) in 1000 years—or in 1,000,000 years?

Timeline

4 billion years ago	By this time, Earth has formed and is partially or completely covered by a liquid water ocean, which it has had ever since.
3.5 billion years ago	Marine life exists on the young Earth.
c. 2 billion years ago	Oxygen revolution by photosynthesis creates an oxygenated atmosphere. Ocean salinity and chemistry stabilize to conditions similar to the present.
470 million years ago	First evidence for land-based life. Life existed solely in the ocean for the vast majority (about 90%) of the planet's history.
210 million years ago	Birth of the Atlantic Ocean by rifting of North America away from Africa and Europe.
c. 1500 B.C.E.	Polynesians had begun long-distance ocean voyaging in the southwestern Pacific.
c. 1200 B.C.E.	Phoenician, Egyptian, and Cretan sailors plied the Mediterranean and into the Atlantic, trading as far away as the British Isles.
c. 200 B.C.E.	In Alexandria, Egypt, Eratosthenes recognized the spherical nature of Earth and calculated the circumference to be 40,250 km, within 8% of the correct value (and far better than Columbus's estimate more than a millennium later). He also created the first recorded marine charts.

150 B.C.E.	Ptolemy's map of the region around the Mediterranean includes surrounding ocean areas; this is the first map to put north at the top and include regular lines of latitude and longitude divided into degrees, minutes, and seconds—just as we use today. Lost to European history for almost 1000 years when the library at Alexandria was destroyed in 415 C.E., Ptolemy's map was rediscovered during the later Crusades and was translated into Latin in 1406.
300–600 C.E.	Polynesian navigators had colonized nearly every inhabitable island in the Polynesian triangle, extending from New Zealand east to Easter Island and north to the extremely remote Hawaiian Islands.
c. 400	Magnetic compass is invented in China.
c. 1002	Leif Ericsson and Vikings reach the North American mainland. Around the same time, Arab sailors explore and establish trade routes in the Indian Ocean.
1200s	Magnetic compass is introduced to Europe.
1405	Chinese admiral Zheng He commands the world's largest fleet with 317 ships manned by 27,000 voyagers traveling across the Indian Ocean and to Arabia.
1492	Columbus sails west across the Atlantic, (re) discovers the island of Hispaniola and the New World accidentally due to his radical underestimate of the size of Earth.

1507..... The Waldseemüller map is published, the first to show "America" and the New World as separate from Asia.

1519–1521..... Magellan's expedition makes the first circumnavigation around the world (Magellan himself dies along the way), ushering in the age of exploration and conquest.

1674..... British chemist Robert Boyle publishes his studies on salinity, temperature, and pressure with depth in *Observations and Experiments on the Saltiness of the Sea*.

1687..... Isaac Newton's *Principia Mathematica* is published, including his gravity-based theory of the tides.

1699..... Edmond Halley (namesake of the famous comet) commands the Royal Navy vessel *Paramour* on the first purely scientific voyage to the South Atlantic to investigate Earth's magnetic field.

1741..... First description of the sea cow, which was hunted to extinction within a generation thereafter, is made by Georg Steller.

1760..... First accurate clock at sea, John Harrison's 4th chronometer, allows accurate determination of longitude for the first time.

1768..... Oceanography as a science begins with the first of 3 expeditions captained by James T. Cook of the British Royal Navy, establishing himself as arguably the first true marine scientist. These expeditions of discovery in the Pacific are the first to include naturalists and systematic botany.

1770..... Benjamin Franklin and Timothy Folger publish their Gulf Stream chart.

1831–1836..... Charles Darwin's voyage on the HMS *Beagle*; he identifies 3 types of coral reef and develops a theory of how atolls form (published in 1842). He also makes the fundamental observations in the Galapagos Islands and elsewhere that lead to his theory of evolution by natural selection.

1840..... Sir James Clark Ross makes the first deepwater sounding in 2425 fathoms (4435 meters) in the North Atlantic.

1872–1876..... HMS *Challenger* embarks on the first true oceanographic expedition, a 4-year, around-the-world voyage of scientific observation, collection, and measurement. Leads to the publication of the 50-volume *Challenger* report, the basis of modern oceanographic science.

1893–1896..... Expedition by Fridtjof Nansen in the *Fram*, intentionally frozen into the pack ice, demonstrates that no Arctic continent existed but, rather, that it is an ice-covered ocean; the expedition also pioneers many modern oceanographic techniques of deepwater sampling and sounding.

1903..... Scripps Institution of Oceanography founded, marking the beginning of the era of dedicated ocean research centers.

1908..... Fridtjof Nansen becomes the first person designated as "Professor of Oceanography," a post he held at Christiania University in Norway.

1912..... Alfred Wegener publishes his theory of continental drift.

1925..... German research vessel *Meteor* makes the first large-scale echo soundings.

1930..... Beginning of deep-submergence science with the first bathysphere submersible to descend more than 1000 feet (William Beebe and Otis Barton).

1932..... International Whaling Commission is founded to address whaling practices and endangerment of whale species.

1943..... Jacques Cousteau and Emile Gagnan invent the SCUBA aqualung to allow divers to stay under water, untethered, for extended periods of time.

1955..... First marine magnetometers to measure strength of magnetic field are used to discover the magnetic striping of the ocean floor.

1957..... First physiographic map of the floor of the North Atlantic Ocean is published by Bruce Heezen and Marie Tharp.

1960..... Don Walsh and Jacques Piccard dive 35,000 feet in the bathyscaphe submersible *Trieste* to the deepest-known point on Earth in the Marianas Trench; Harry Hess and Robert Dietz publish their hypothesis of seafloor spreading.

1961..... Project Mohole, the first deep-sea drilling research project, is a pioneering but ultimately unsuccessful effort to drill down to Earth's mantle in the Pacific Ocean. Led to the development of the international Deep Sea Drilling Project and it's successors from 1968 to the present day.

1963..... Vine and Matthews propose that regular variations in the magnetic field support the hypothesis of seafloor spreading.

1965..... Seafloor spreading, continental drift, and subduction are assembled into the new theory of plate tectonics by J. Tuzo Wilson, Jason Morgan, and others.

1968..... Deep Sea Drilling Project begins with *Glomar Challenger* carrying out the first extensive scientific drilling to sample the ocean floor.

1970..... National Oceanic and Atmospheric Administration (NOAA) is established in the United States and takes on the responsibility for mapping and researching the oceans.

1977..... During *Alvin* submersible dives to the Galapagos rift zone, seafloor hydrothermal vents (black smokers) and associated chemosynthetic biological communities are discovered; First physiographic map of the entire ocean floor is published by Heezen and Tharp; even at this time, much of it had to be extrapolated through artistic license.

1978..... Seasat, the first satellite devoted to oceanographic observations, is launched.

1983..... Global Positioning System (GPS) is first made available for public use, revolutionizing ocean (and land) navigation.

1985..... Shipwrecked RMS *Titanic* is found in 3800 meters depth using sidescan sonar and is photographed using the unmanned deep-submergence vehicle *Argo* (Robert Ballard and photographer Emory Kristof).

1994..... Convention on the Law of the Sea (signed in 1982) comes into effect, defining territorial waters as a maximum of 12 nautical miles (22 km) from the coast, Exclusive Economic Zones (EEZ) for fishing and construction as no more than 200 nautical miles (370 km), and a nation's continental shelf and drilling rights as extending a maximum of 350 nautical miles (650 km).

1995..... Declassification of Geosat satellite radar altimetry (data gathered starting 1985) allows David Sandwell and Walter Smith to map the worldwide ocean bathymetry in unprecedented detail, producing the first true global map of the shape of the ocean floor.

2002..... End of the first World Ocean Circulation Experiment (WOCE, began in 1990), a multinational comprehensive study of ocean currents and their interaction with the atmosphere.

2004..... Tsunami generated by a subduction earthquake off the west coast of Sumatra, Indonesia, causes widespread devastation in the Indian Ocean basin and the loss of 250,000 lives.

2007..... Fourth Intergovernmental Panel on Climate Change (IPCC) report is issued, which reports on the increasing heat content of the ocean, the accelerating pace of sea-level rise, and progressive ocean acidification as significant changes in the ocean environment that are caused by the addition into the atmosphere of carbon dioxide and other greenhouse gases from fossil fuels.

2010..... Completion of 10-year Census of Marine Life, involving 2700 scientists from more than 80 countries and 540 expeditions to comprehensively inventory the marine biology of the ocean.

Glossary

abyssal: Depth range of 3000–6000 meters in the water or on the bottom of the ocean.

abyssal plain: The vast, open expanse of relatively level bathymetry that comprises most of the ocean floor.

Acoustic Doppler Current Profiler (ADCP): A device that measures current speed by measuring the Doppler frequency shift of sound waves reflected back from particles in the water.

active transport: A process by which cells use energy to move solutes against the concentration gradient across membranes.

ahermatypic coral: Soft coral that makes no hard reef structures.

albedo: The fraction of solar energy reflected by a surface (as opposed to energy absorbed).

amphidromic circulation: Tidal movements as affected by Coriolis forces, causing high water to circulate around a node, or no-tide point.

anadromous fish: Fish that spend part of their life cycle in freshwater and part in the ocean, such as salmon.

Antarctic Bottom Water: The coldest, saltiest, and densest water mass in the ocean that forms off the Antarctic continental shelf and spreads over the base of the entire Atlantic Ocean.

aphotic zone: The range of water depths into which no sunlight penetrates; the dark zone of the ocean.

aqueous solution: A mixture of compounds in water that are dissolved or separated into their charged ionic forms and are bonded to the water molecules through hydrogen bonds.

asthenosphere: The slow-flowing portion of Earth's mantle on which the rigid plates of lithosphere float and move.

atmospheric circulation cells: Large-scale, closed loops of overall mean airflow distributed according to latitude.

atoll: Ring-shaped group of coral islands or reefs formed around a now-submerged volcanic island.

autotroph: Any organism that produces carbohydrate food from primary sources of energy.

azoic zone: Edward Forbes's briefly popular theory of the mid-1800s that no life existed below depths of about 900 meters; the theory was soon disproven by trawls and dredges.

baleen: Horn-like fibrous plates used by Mysticeti whales to strain plankton from seawater.

bathyal: Depth range of 1000–3000 meters in the water or on the bottom of the ocean.

bathymetry: Measurement of water depth below the sea surface; an inverse equivalent to topography on land.

benthic: The environment on or in close proximity to the water on the bottom of the ocean.

berm: The prominent break in slope on many beaches that marks the highest elevation of wave washing.

biogenous sediment: Sediment originating as the hard parts of marine organisms.

bioluminescence: The process of production of light by an organism, used for camouflage, defense, and attraction of prey and mates.

biomagnification: The exponential increase in the concentration of toxic compounds in animal tissues at successively higher trophic levels.

black smoker: One type of hydrothermal vent in which the hot-water plume is laden with mineral particles that give it the appearance of smoke.

blowout: The uncontrolled release of gas, oil, and/or water under pressure from a well.

breakwater: A rocky barrier constructed parallel to shore and just off shore to protect from wave action.

building sea: Area of surface water where wind action is actively creating and growing new waves.

bycatch: Non-targeted fish caught collaterally during commercial fishing; often discarded as noneconomic.

calcite compensation depth (CCD): Depth below which the water will dissolve calcareous shells such that calcareous ooze does not accumulate as a sediment.

capillary waves: Ripples in water defined by the dominance of surface tension as the restoring force.

caprock: Non-permeable marine rock that can trap in petroleum or natural gas that would otherwise buoyantly rise up through denser water and escape to the surface.

celerity: The speed at which a water wave moves; equal to wavelength divided by wave period.

cephalopod: Mollusks including squid, octopus, cuttlefish, and nautilus that are characterized by bilateral symmetry, a prominent head exhibiting many tentacles.

Cetacea: Taxonomic group of marine mammals descended from land ungulates that includes dolphins, porpoises, and whales.

chemical (hydrogenous) sediment: Sediment formed by precipitation of minerals from seawater.

chemical oceanography: Discipline primarily concerning the composition of seawater and distribution of its chemical constituents.

chemoautotroph: Organism that manufactures food (carbohydrates) from the energy of chemical bonds.

chemosynthesis: Production of carbohydrate food energy by extraction from the breaking of chemical bonds.

Chondrichthyes: The taxonomic class comprised of all cartilaginous fish, such as sharks and skates.

chronometer: Precise clock originally used to determine longitude based on timing of local noon.

coccolithophorid: An abundant group of calcareous algal phytoplankton; their remains are responsible for chalk.

continental drift: The early 20th-century theory that the continents had moved with respect to one another over Earth's surface through geologic time; this theory is now superseded by the theory of plate tectonics.

continental margin: The offshore region extending from sea level to the abyssal plain; comprised of the continental shelf, slope, and sometimes rise.

continental rifting: The breaking up of a continent along a narrow zone of faulting and volcanism as a beginning stage of new mid-ocean ridge formation.

continental shelf: The offshore extension of the land of nearly flat average slope, extending to a depth of about 200 meters.

continental slope: The relatively steeply sloping region of the ocean floor that extends downward from the shelf edge to meet the abyssal plain.

copepod: Very small crustacean zooplankton that are widespread in the pelagic ocean.

Coriolis effect: The tendency of any object in motion on Earth to deviate from a straight-line course due to the rotation of the planet.

covalent bond: The strong bond formed when 2 or more atoms share common electrons; for example, the 2 hydrogen atoms and 1 oxygen atom of a water molecule.

CTD: An instrument lowered into the water to make continuous measurements of conductivity (for salinity), temperature, and depth.

ctenophore: Very common pelagic gelatinous organism, also known as comb jellies.

cyanobacteria: The single-celled organisms that carry out photosynthesis; likely the agents of the oxygen revolution.

DART station: Stands for Deep-ocean Assessment and Reporting of Tsunamis. A buoyed transmitter with a seafloor pressure sensor that can detect tsunami waves as they travel across the open ocean, providing early warning information.

deep-sea fan: Accumulation of a wedge- or fan-shaped pile of sediment at the base of continental slopes.

deep-sea trench: Narrow, arcuate features extending thousands of kilometers of especially deep bathymetry that form at subduction zones, where oceanic crust bends to descend into the mantle.

deepwater wave: A wave in water deeper than 1/2 the wavelength.

density stratification: The process by which the early Earth separated into concentric layers with denser iron-rich material sinking to form the core and lighter elements and rock compounds forming the mantle and crust.

desalination: Process of removing salts from seawater by distillation or reverse osmotic pressure.

diatom: A major and abundant group of siliceous single-celled phytoplankton; they produce glassy frustules.

diffusion: The spreading and dilution of solutes by movement from areas of higher concentration to lower concentration.

dinoflagellate: A major and abundant group of siliceous single-celled phytoplankton; they have whip-like flagella.

disphotic zone: The region of the water column in which light is present but insufficient for photosynthesis.

diurnal tide: A single daily cycle of one high and one low tide.

downwelling: The movement of surface water downward, depressing the thermocline due to either high density or Ekman-transport effects.

echo sounding: Determination of bathymetric water depth by precise timing of a sound wave emitted by a ship and reflected from the water bottom.

Ekman transport: The tendency of wind-driven surface currents to move at an oblique angle to the wind direction, caused by the Coriolis effect acting on the water. The effect increases with depth, creating the variation in motion direction known as the Ekman spiral.

epifauna: Benthic organisms that dwell on or above the sea floor.

equatorial divergence: The tendency of wind-driven surface waters to move in opposite directions just across the equator because of the opposite Coriolis effect in the Northern and Southern hemispheres.

estuary: Coastal body of water where seawater and stream- or river-supplied freshwater mix.

euphotic zone: The uppermost portion of the photic zone with sufficient sunlight for net gain in energy through photosynthesis.

eustatic sea level: The globally averaged elevation of the sea surface.

eutrophication: Conditions of overabundance of nutrients in the water usually due to fertilizer runoff, leading to harmful algal blooms and hypoxia.

extraterrestrial (cosmogenous) sediment: Sediments with an extraterrestrial origin that fall into the ocean from space as meteorites or dust.

extratropical cyclone: Rotating mass of air formed by the disturbance of the boundary between polar and Ferrell cells; includes the northeasters.

fetch: Linear distance over which relatively constant wind blows, forming wind waves.

fissipeds: Marine mammal group including sea otters; in the same order as dogs, cats, bears, and weasels.

fjord: Glacially formed deep and steep-walled valley flooded by the sea.

food web: Representation of the feeding relationships and flow of energy through a biological community.

fracture zone: The inactive trace of a past transform fault beyond the overlap of offset ridges; they may extend thousands of kilometers across the ocean floor.

general circulation models: Supercomputer simulations of the circulation of heat and compounds in the ocean-atmosphere system; used to simulate climate fluctuations and long-term trends.

geochemistry: The science that studies the chemical composition of rocks as a clue to past conditions or geologic processes.

geostrophic gyre: The hemisphere-scale surface-current loops set up in each ocean basin that are dynamically balanced by competing effects of Ekman transport and gravity.

greenhouse effect: The physical property of some atmospheric gases to absorb and trap heat from the Sun's radiation shining on Earth.

guyot: A characteristically flat-topped seamount that was once eroded by wave action as an island and is now entirely submerged.

habitat: The physical environment in which an organism lives.

hadal: Depth range greater than 6000 meters in the water or on the bottom of the ocean; the deepest locations in the ocean.

halocline: A strong gradient in salinity with depth; largely coincides with the pycnocline and thermocline.

hard stabilization: Construction of a solid barrier such as a seawall to lessen or delay the effects of beach or sea-cliff erosion.

heat capacity: The amount of heat energy absorbed by a substance to raise its temperature a specified amount, also known as thermal capacity.

hermatypic coral: Coral that secretes carbonate and builds up reefs.

heterotroph: Any organism that consumes organic matter produced by others.

holdfast: The anchor of a kelp seaweed that fixes it to the substrate, as roots do for vascular plants.

holothurian: The sea cucumber or sea pig, a soft benthic echinoderm that scavenges the mud of the sea floor.

hydrogen bond: The weak bond formed when polar ions or molecules are linked by attraction of their oppositely charged regions.

hydrothermal vent: A seafloor hot spring where superheated, chemically laden water is discharged from the oceanic crust.

hypoxic zone: Any region in the ocean of extremely low oxygen availability due to fertilizer runoff; an example is in the Gulf of Mexico off the mouth of the Mississippi River.

hypsometric curve: A graph showing the cumulative area of Earth's surface above any given elevation, above or below sea level.

infauna: Benthic organisms that dwell within the sea floor.

krill: Crustacean zooplankton, very abundant in Antarctic waters in particular.

lagoon: Shallow saltwater region trapped between the beach dune zone and the mainland area.

latent heat: The heat energy that must be absorbed or released to change the state of a material by evaporation or freezing, producing no temperature change.

lithosphere: The rigid outer portion of Earth's crust and uppermost mantle that makes up the tectonic plates.

longshore bar: Sandbar parallel to the coast and just offshore in the tidal range.

longshore drift: Net transport of sediment parallel to the coast due to prevailing wave directions and variable swash and backwash on the beach.

magnetometer: A device that measures the strength and orientation of Earth's magnetic field.

manganese nodule: Roughly spherical particle formed as manganese oxide precipitates from seawater over time.

mariculture: Fish farming, or growing fish for food in ocean-water tanks or pens.

marine snow: Clumps of whitish organic detritus that form a constant "snowfall" to the sea floor in deepwater environments; fuels scavenger ecosystems.

maximum sustainable yield: The amount of a given target species that can be caught each year without long-term depletion of the stock.

mesoglea: Translucent, jellylike gel that makes up the bulk of organisms like jellyfish.

mesopelagic zone: The dimly lit region of the water column; also called the disphotic zone or the twilight zone.

microbial loop: A producer-consumer food web in the ocean consisting entirely of bacteria and largely independent of the conventional ecosystem.

microtektite: Tiny glassy particles produced by impact melting when an asteroid hits Earth.

mid-ocean ridge: The globe-encircling mountain range where seafloor spreading occurs by volcanic activity creating new oceanic crust.

Miller-Urey Experiment: A 1955 laboratory study that demonstrated that organic compounds could be spontaneously generated from inorganic carbon compounds and energy.

mixed tide: Most common type of daily tide cycle, exhibiting 2 tidal cycles per day with differing highs and lows.

monsoon: Seasonal weather pattern typified by heavy rain resulting from onshore flow of warm, humid air drawn in by rising air heated over mountain ranges in the summer, especially in the Indian subcontinent and Himalayan mountain front.

multibeam bathymetry: Bathymetric mapping done by echo sounding using a fan of narrow acoustic beams to image a strip of the ocean floor.

neap tide: The relatively small range between high and low tide at times of quarter Moon due to destructive interference of solar and lunar gravity.

nekton: All organisms that actively swim in the ocean (e.g., fish, marine mammals, cephalopods, and more).

nematocysts: Also known as cnidocytes, the stinging cells of many jellyfish and other cnidarians.

neritic: The region on or over the continental shelf.

Niskin bottle: A device to take a water sample from a specified depth in the water column that has 2 open ends that can be triggered to close and seal in a water sample.

North Atlantic Deep Water: The cold, saline water mass that forms in the North Atlantic and Arctic oceans that is responsible for most of the volume of the deep ocean.

ocean acidification: The increase in acidity of seawater that is developing as a result of increased dissolved carbon dioxide.

ocean basin: The container for the ocean; the region underlain with oceanic crust and bounded by continental slopes.

oceanic crust: The crust of Earth, which is formed at mid-ocean ridges by lava and magma welling up from the mantle that forms the geologic substrate of most of the ocean floor.

oceanography: The scientific study of the oceans, encompassing the application of the disciplines of physics, chemistry, biology, and geology to all aspects of the global ocean.

ocean thermal energy conversion (OTEC): A pilot technology to generate energy by exploiting the temperature difference between warm, near-surface water and cold, deep water drawn up to the surface.

oil boom: A floating curtain of plastic placed into the water to contain spilled oil on the surface of the water.

ooze: Sediment of the deep-sea floor that primarily originated from accumulated shells and skeletons of plankton; can be calcareous (carbonate-based) or siliceous (silica-based) ooze.

orbital motion: The circular path taken by a water particle as a wave passes by, moving it first back and upward then forward and down to return to its starting point.

osmoregulation: Biological process of controlling internal salinity and other chemical balances for optimum metabolism.

osmosis: A passive process causing net movement of solvent (water) across a membrane separating 2 solutions of different concentration level, tending to equalize their concentration.

Osteichthyes: The taxonomic class comprised of all bony fish.

oxygen-minimum zone: Depth range in the ocean where available oxygen is lowest, beneath the photic zone but above the cold, very deep waters.

oxygen revolution: The wholesale modification of Earth's atmosphere from an oxygen-poor one to the present oxygen-rich one between 3.5 and 0.8 billion years ago.

paleoceanography: Discipline that involves studying ancient past currents, climate, and the state of the ocean from thousands to billions of years ago.

Panthalassa: The single large ocean hypothesized by Alfred Wegener that surrounded Pangaea, the unified single continent that has since rifted apart.

pelagic: The open-water environment that is away from coasts and off the continental shelf.

pelagic longline fishing: Fishing method employing baited hooks on a kilometers-long main fishing line, used for fish that have high trophic levels—such as swordfish and tuna.

persistence: The length of time a pollutant lasts in an environment.

photic zone: The sunlit upper layer of ocean water.

photophores: The organs that produce light in bioluminescent organisms.

photosynthesis: The biological process of capturing solar energy by using it to make carbohydrates as food.

physical oceanography: Discipline primarily concerning the movement and physical properties of water in the oceans.

pinnipeds: Marine mammal group including seals, sea lions, and walruses; in the same order as dogs, cats, bears, and weasels.

piston core: A cylindrical sample of the ocean-floor sediments taken by lowering a hydraulically activated, weighted sampling tube from a surface-research ship.

planetesimals: Small asteroid-like clumps of rock orbiting around an early Sun that accreted together by gravity to form Earth and other rocky planets.

plankton: All organisms that drift with water movements and currents passively.

plate tectonics: Scientific theory on the movement and evolution of Earth's outer layers over geologic time.

polyps: The individual coral animals, similar to sea anemones, that collectively make up the colony in a coral head.

primary production: The creation of biomass through photosynthesis or chemosynthesis.

principle of constant proportions: The ratio of major salts in seawater is everywhere the same in the world's ocean—though concentration (salinity) may differ. Also known as Forchhammer's principle.

Project Mohole: The first deep-sea drilling research project; a pioneering but ultimately unsuccessful 1961 effort to drill down to Earth's mantle in the Pacific Ocean.

pycnocline: A strong gradient in density of seawater versus depth.

reservoir rock: Porous marine rock or sediment layers that can hold large amounts of petroleum or natural gas.

residence time: The amount of an element in the ocean divided by the rate at which it is added or removed; a measure of the average time the element stays in seawater.

respiration: Metabolic process of consuming energy by breakdown of carbohydrates with oxygen to fuel activity, releasing carbon dioxide.

river-dominated delta: A river mouth in which the strong flow from land determines the pattern of sediment deposition and channel geometry.

rogue wave: Any wave or short series of waves at least 2 times larger than prevailing waves in the area and time—and larger than the theoretical maximum for a fully developed sea.

salinity: The total amount of dissolved solids in water, expressed by weight per unit volume.

salp: A tubular, gelatinous animal that lives either as an individual or as a colony that is common in equatorial waters.

salt evaporation: Production of sea salt for consumption by evaporation of seawater in open ponds.

satellite altimetry: Measurement of the elevation of the sea (or land) surface precisely using space-based radar-signal reflection timing.

seamount: Volcanic mountain that rises above the surrounding ocean floor but is submerged below sea level.

sea stack: Rocky outcropping near the shore but isolated from the mainland created by erosional retreat of sea cliffs over time.

sediment: Particles of inorganic or organic matter that accumulate in a loose, unconsolidated form.

semidiurnal tide: A daily cycle of 2 high and 2 low tides.

sensible heat: Heat energy that results in a change in temperature.

sessile: Animals unable to move about that are usually permanently fixed to their substrate, such as barnacles or corals.

sextant: Instrument used to measure the angle above the horizon of celestial objects that is used in navigation.

shallow-water waves: Formally, all waves in water shallower than $1/20^{th}$ of the wavelength.

siphonophore: An order of Cnidaria that are colonial animals; one example is the Portuguese man-of-war.

Sirenia: Taxonomic group of marine mammals that includes manatees and dugongs.

soft stabilization: Addition of sand to a beach through beach replenishment or nourishment to mitigate beach erosion.

solar nebula: The rotating cloud of gases and particles from which the Solar System formed.

spring tide: The relatively large range between low and high tide at times of constructive interference of lunar and solar gravity during full and new moons.

stick chart: Maplike representation of islands, waves, and ocean currents used in navigation by Micronesian and Polynesian seafarers.

subduction zone: Location where oceanic plate lithosphere (the sea floor and its underpinnings) descend into Earth's mantle, consuming the tectonic plate.

submarine canyon: Any offshore canyon on the continental slope that is formed by erosion due to flows of sediment along the bottom in turbidity currents.

substrate: The sediment or rock base forming part of a benthic organism's habitat.

swell: Waves that have left the area of development and are propagating across the sea surface.

swim bladder: Gas-filled chambers many fish have beneath their spine to maintain buoyancy in the water.

terrigenous sediment: Sediment originating from land that is input into the ocean either by water- or wind-borne transport.

thermal expansion: The increase in volume of water as it becomes warmer; specifically used to refer to the component of sea-level rise due to this effect as heat content of the ocean changes.

thermocline: A strong gradient in water temperature versus depth that separates warm surface waters from the vast volume of cold, deep water.

thermohaline circulation: Gravity-driven movement of deepwater masses due to the density differences controlled by salinity and temperature.

tidal bore: An inrushing high-tide wave that funnels up a confined river or estuary.

tide-dominated delta: A river mouth in which the waves and tides determine the pattern of sediment deposition and channel geometry.

toxicity: The amount of a pollutant necessary to cause some form of damage in an ecosystem or organism.

trade winds: Prevailing easterly winds centered on 15° latitude north and south.

tragedy of the commons: Concept articulated by Garrett Hardin that when a resource is available to a large group in common, it benefits each member to maximize his or her use—even if it would be better for everyone to limit their use. Applied to the problem of fishery management.

transform fault: Location where one plate slides past another on Earth's surface—neither creating nor consuming plate area—especially those between offset spreading ridge segments.

transverse current: The generally east-west flowing surface currents that link the boundary currents and also account for the Antarctic Circumpolar Current (also known as the West Wind Drift).

trophic level: A scale of how many steps of consumption an organism is removed from primary production.

tropical cyclone: Rotating mass of tropical, low-pressure air with heavy winds and rainfall fueled by sea-surface heat; includes hurricanes and typhoons.

tsunami: A wave train produced by displacement of water due to sudden mass movement of the sea floor caused by an earthquake or undersea landslide.

tubenose: Taxonomic group of far-traveling marine birds including albatrosses, shearwaters, and petrels.

turbidity current: Flow of suspended sediment-laden water down the ocean floor that is driven by density and gravity.

upwelling: The movement of cold, deeper water upward to the sea surface when surface waters are drawn away by divergence or Ekman-transport effects.

volcanic outgassing: The release of water, carbon dioxide, nitrogen, and other gases from Earth's interior at volcanoes.

Wadati-Benioff zone: The planes of earthquakes extending deep into Earth that mark the location of the consumed plate slab from subduction.

wave-cut platform: A near-flat bedrock plane cut by wave action eroding the coast between high- and low-tide levels.

wave period: The time elapsed from the passage of one wave crest to the next (or any equivalent points on a cyclical wave).

wave refraction: Bending of the orientation of wave crests by differential wave speed caused by local differences in water depth.

wind waves: Waves caused by wind drag on the water surface and defined by the dominance of gravity as the restoring force.

zooxanthellae: Microscopic dinoflagellate photosynthesizers that live symbiotically and are hosted by coral polyps.

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Greenberg, Paul. *Four Fish: The Future of the Last Wild Food*. New York: Penguin, 2010. Greenberg's investigation of global fisheries touches on all the topics of overfishing, industrial fish farming, and the ongoing "gold rush" of wild tuna, showing how 4 fish—salmon, tuna, cod, and bass—dominate the seafood world.

Heezen, Bruce, and Charles Hollister. *The Face of the Deep*. New York: Oxford University Press, 1971. Published in 1971, an atlas and gallery of the pioneering photographs of the ocean floor by the scientists who made them.

Hohn, Donovan. *Moby-Duck: The True Story of 28,800 Bath Toys Lost at Sea and of the Beachcombers, Oceanographers, Environmentalists, and Fools, Including the Author, Who Went in Search of Them*. New York: Viking, 2011. The subtitle says it all. A whimsical odyssey exploring the fate of the bath toys and other flotsam lost at sea.

Holthuijsen, Leo H. *Waves in Oceanic and Coastal Waters*. Cambridge: Cambridge University Press, 2010. An advanced treatise on the physics of ocean waves.

Horwitz, Tony. *Blue Latitudes: Boldly Going Where Captain Cook Has Gone Before.* New York: H. Holt, 2002. Equal parts biography of Captain Cook and travel narrative of the Polynesian world today, this volume provides greater insight into Cook as an explorer and as an Enlightenment figure than do many of the more scholarly biographies. Along the way, Horwitz sheds light on the changes Cook's contact wrought on the people of the Pacific islands.

Hsü, Kenneth J. *The Mediterranean Was a Desert: A Voyage of the* Glomar Challenger. Princeton, NJ: Princeton University Press, 1987. An account of one voyage of the *Glomar Challenger*, a deep-sea scientific drilling vessel, by one of the scientists who was there. It provides insight into how sedimentary records tell us about past conditions on Earth and in the sea.

Kaharl, Victoria A. *Water Baby: The Story of* Alvin. New York: Oxford University Press, 1990. A "biography" of the famous deep-diving submarine that made so many of the fundamental discoveries in the abyss from the 1960s into the 21st century, including the wreck of the *Titanic* in 1985.

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Lawrence, David M. *Upheaval from the Abyss: Ocean Floor Mapping and the Earth Science Revolution*. 2002. The story of sonar, bathymetry, and the unveiling of the shape of the ocean floor that heralded the plate-tectonic revolution.

Medwin, Herman. *Sounds in the Sea: From Ocean Acoustics to Acoustical Oceanography*. New York: Cambridge University Press, 2005. Comprehensive and technical, this textbook covers the whole field of sound in the ocean.

Melville, Herman. *Moby Dick; or, The Whale*. New York: Harper & Brothers, 1851. Read this odd and amazing novel (again) and discover Melville's amusing and lively description of the characters of the Nantucket whaling community—and of Moby Dick himself. I give you permission to skim or even skip over all the cetacean detail in the middle, but it's worth the effort to get to the end.

Menard, Henry W. *The Ocean of Truth: A Personal History of Global Tectonics*. Princeton, NJ: Princeton University Press, 1986. The story of how the plate-tectonics scientific revolution came to pass by one of the scientists who made it happen.

Miller, Charles B. *Biological Oceanography*. Malden, MA: Blackwell Publishing, 2004. A modern reference and comprehensive textbook on marine biology.

Morrissey, John F., and James L. Sumich. *Introduction to the Biology of Marine Life*. 10th ed. Sudbury, MA: Jones & Bartlett Learning, 2010. A classic and standard text, comprehensively covering in detail the topics of marine life, food webs, ecology, and more.

Murphy, Dallas. *To Follow the Water: Exploring the Ocean to Discover Climate*. New York: Basic Books, 2008. A journalist goes to sea for a month with physical oceanographers and elucidates ocean currents and the link to heat transport on the planet.

Nash, J. Madeleine. *El Niño: Unlocking the Secrets of the Master Weather-Maker*. New York: Warner Books, 2003. A science journalist's investigation of the causes and effects of the gigantic Pacific weather system, using the record-breaking 1998–1999 event as a primary example.

National Oceanic and Atmospheric Administration (NOAA). *Hidden Depths: Atlas of the Oceans*. New York: HarperCollins, 2007. A beautifully illustrated and informative atlas coproduced by the OAA and the Smithsonian as they developed the Sant Hall of Ocean Sciences in the Smithsonian Museum of Natural History, this volume complements the course very well. Highly recommended.

Nouvian, Claire. *The Deep: The Extraordinary Creatures of the Abyss*. Chicago: University of Chicago Press, 2007. This is a bit of a coffee-table book, but the stunning photography of hundreds of only recently discovered organisms makes it well worth a look.

Open University. *Ocean Circulation*. 2nd ed. Oxford: Butterworth-Heinemann, 2001. For those who want to delve deeper into the surface and deep flow in the oceans, this is a physical oceanography text without overreliance on mathematics.

———. *Seawater: Its Composition, Properties and Behaviour*. 2nd rev. ed. Oxford, UK: Butterworth-Heinemann, 2004. A complete textbook on the properties of ocean water for the seriously interested.

Oreskes, Naomi. *Plate Tectonics: An Insider's History of the Modern Theory of the Earth*. Cambridge, MA: Westview Press, 2003. A collection of essays written by many of the scientists who were there at the birth of plate tectonics that is stitched together by the author, a historian of science.

Parker, Bruce. *The Power of the Sea: Tsunamis, Storm Surges, Rogue Waves, and Our Quest to Predict Disasters*. New York: Palgrave Macmillan, 2010. A more in-depth—but still layperson's—treatment of destructive waves in the ocean.

Philbrick, Nathaniel. *In the Heart of the Sea: The Tragedy of the Whaleship* Essex. New York: Penguin, 2001. The story of the 19th-century Pacific whaling industry told using the device of examining a microcosm—the wreck of the *Essex* that was the inspiration for *Moby Dick*.

Pilkey, Orrin H., William J. Neal, Joseph T. Kelley, and J. Andrew G. Cooper. *The World's Beaches: A Global Guide to the Science of the Shoreline*. Berkeley: University of California Press, 2011. An illustrated introduction to the anatomy of beaches and shorelines and the effects of sea-level rise upon them.

Pilkey, Orrin H., and Rob Young. *The Rising Sea*. Washington DC: Island Press/Shearwater Books, 2009. A brief, clear, and very accessible account of the causes and effects of the accelerating sea-level rise that is now impacting shorelines in the United States and around the world.

Prager, Ellen. *Chasing Science at Sea: Racing Hurricanes, Stalking Sharks, and Living Undersea with Ocean Experts*. Chicago: University of Chicago Press, 2010. An inspirational and lively window to the real life of marine scientists making discoveries and having adventures.

———. *Sex, Drugs, and Sea Slime: The Oceans' Oddest Creatures and Why They Matter*. Chicago: University of Chicago Press, 2011. Wonderfully entertaining and informative look at the life and times of sea cucumbers, octopi, lobsters, and many others. Prager really brings these denizens of the deep to life in an unmatched way.

Pugh, David. *Changing Sea Levels: Effects of Tides, Weather and Climate*. New York: Cambridge University Press, 2004. Textbook-level material for more in-depth examination of tidal theory as well as storm surges, climate, and sea-level rise.

Rogers, A. D., and D.d'A Laffoley. "International Earth System Expert Workshop on Ocean Stresses and Impacts." Summary report. International Programme on the State of the Ocean (IPSO). Oxford, 2011. 18 pp. The current state of knowledge of ocean heat content and temperature change, acidification, and sea level is a rapidly changing target; at the time of this writing, this was an up-to-date and concise summary.

Safina, Carl. *A Sea in Flames: The Deepwater Horizon Oil Blowout*. New York: Crown Publishers, 2011. A marine biologist and conservationist gives his take on the 2010 Gulf of Mexico disaster, arriving at some perhaps counterintuitive conclusions about the nature of society's impact on the Gulf ecosystem.

———. *The View from Lazy Point: A Natural Year in an Unnatural World*. New York: Henry Holt and Company, 2011. A conservationist view of the damage to the ocean environment that modern society is causing, leavened with the author's optimism that the world still contains vast natural beauty and vibrant ecosystems.

Schreiber, Elizabeth A., and Joanna A. Burger, eds. *Biology of Marine Birds*. Boca Raton, FL: CRC Press, 2001. A comprehensive and detailed authoritative source by experts in the field.

Sheets, Bob, and Jack Williams. *Hurricane Watch: Forecasting the Deadliest Storms on Earth*. New York: Vintage, 2001. A history of the scientific progress in predicting and forecasting hurricanes and typhoons.

Sobel, Dava. *Longitude: The True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time*. New York: Walker & Company, 1996. A fascinating short account of how the need for navigation at sea led to the development of accurate clocks, providing surprising insights into British class distinctions and science in the 18th century along the way.

Sverdrup, Keith A., and E. Virginia Armbrust. *Introduction to the World's Oceans*. 10th ed. Boston, MA: McGraw-Hill, 2008. A comprehensive textbook that would make a fine companion to the course—either instead of or in addition to Garrison's *Essentials of Oceanography*.

Ulanski, Stan. *The Gulf Stream: Tiny Plankton, Giant Bluefin, and the Amazing Story of the Powerful River in the Atlantic*. Chapel Hill: University of North Carolina Press, 2008. The Gulf Stream, from Franklin to satellites, with lots of marine life thrown in as well.

Van Dover, Cindy Lee. *The Ecology of Deep-Sea Hydrothermal Vents*. Princeton, NJ: Princeton University Press, 2000. An expert writes an accessible text on the unique life at the black smokers and other mid-ocean ridge vents.

Videler, John J. *Fish Swimming*. New York: Chapman & Hall, 1993. A biology textbook on the processes of swimming and hydrodynamics of fin and other fish.

Walker, Gabrielle. *An Ocean of Air: Why the Wind Blows and Other Mysteries of the Atmosphere*. Orlando, FL: Harcourt, 2008. Atmospheric circulation at the level of a popular science account.

Yergin, Daniel. *The Prize: The Epic Quest for Oil, Money, and Power*. New York: Free Press, 2009. A sweeping history of the oil industry and its impact on virtually every aspect of modern life.